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# MULTI-HIT DISPERSION OF OIL SPILLS

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# MULTI-HIT DISPERSION OF OIL SPILLS

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## ABSTRACT

An experimental program is described in which three crude oils (EPS Standard Oil, Norman Wells crude oil and a Beaufort Sea crude oil) were subjected to chemical dispersion using three commercial products (BP MA700, Corexit 9527 and Corexit 9550) in laboratory test systems. The experiments were designed to test how dispersion efficiency was affected by applying the dispersant in one dose or several repeated doses of less individual amount but constant total amount. The data were fitted to a simple mathematical model. It was concluded that the hoop dispersion apparatus is the only one suitable for measurement of single and multi-hit dispersion. Further, for this system and the oil-dispersant combinations tested there was no significant consistent difference in final effectiveness when the same quantity of dispersant was applied accurately to oil in one dosage or in several smaller "multi-hit" dosages totalling the same amount. Oceanic conditions may, however, occur in which multi-hit application is less effective. For example the oil may weather appreciably, it may form water-in-oil emulsion and it may spread to form larger, thinner slicks which can not be dispersed as efficiently. Some implications for dispersant application strategies are discussed and it is concluded that when feasible, single hit dispersion is preferable, but when only multihit dispersion is feasible, little or no penalty is paid for this method of application.

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## 1. INTRODUCTION.

Recent sea trials of dispersant effectiveness in Canadian, U.S., U.K., Norwegian and French waters have shown that dispersants are often only partially effective in removing an oil slick from the water surface. A typical slick may be treated with a dispersant at a ratio of 1 volume dispersant to 20 volumes of oil and after 30 minutes some 20 to 30 percent of the oil is emulsified into the water column. This contrasts with laboratory effectiveness tests in which 80 to 100 percent may be emulsified under apparently similar conditions. The background to this issue has been reviewed recently by Mackay et. al. (1984, 1985).

One "remedy" is to treat the slick repeatedly with more dispersant in the expectation that on each occasion more oil will be dispersed, until eventually the slick is totally emulsified. There are obvious disadvantages to this approach but in certain situations it may be the only feasible course of action. A number of factors influence the desirability of this "multi-hit" approach.

- o More dispersant may be needed, with corresponding cost and stockpile implications.
- o There may be logistic constraints in the case of a large spill in which there is a limitation on the available dispersant application capacity.
- o Dispersants may influence the spreading behaviour of a slick (generally increasing the spill area) thus repeated application may be less feasible.
- o The oil will "weather" during the intervals between applications causing a possible reduction in efficiency.
- o It may be impossible to apply the required dosage of for example 100 L/ha in one flight pass, thus several passes may be needed.
- o Repeated application may result in better targetting.
- o In a study of oil dispersion in the presence of ice using a "hoop" or radial wave apparatus, Mackay et. al. (1979) applied dispersant repeatedly at an individual ratio of 1/27. The results are shown in Figure 1.1 (which is Figure 27 of the original report), the accompanying text being as follows.
  "A final test involved the repeated application at 0, 4 and 8 hours of dispersant to oil at 0 deg.C with no ice present. The results in Figure 27 are puzzling in that there was little additional dispersion. It appears that oil which has been subjected (unsuccessfully) to dispersion subsequently becomes more difficult to disperse. Part of this may be attributable to viscosity increase and water-in-oil emulsion formation but the results are not sufficiently complete or conclusive to enable this effect to be explained or even proved.
  The general conclusion is that dispersants should be added to oil only under conditions of turbulence such that dispersion will occur within a few hours. There is some evidence that there is little merit in adding dispersant in the hope of its action taking place some hours or days later. It is suspected that dispersant

slowly partitions out of the oil into the water, and the potential for dispersion is lost. This is clearly of considerable countermeasures significance and requires further examination. Further, there is evidence that the best strategy is to disperse the oil as fully as possible in one dosage since returning later to administer more dispersant to undispersed oil may prove less efficient.
It is emphasized that this work has been exploratory in nature and while it has been successful in identifying some of the effects discussed above, it is too early to draw definite conclusions."

If this conclusion is broadly applicable it has important implications for dispersion as a countermeasure. A factor in this issue may be that the nature of the oil is changed by the introduction of the dispersant or between applications in one of several ways.

- Volatiles may be depleted by evaporation.
- Aromatics may be depleted by dissolution, this being particularly important if an appreciable fraction of the oil is emulsified into the water column where it is maintained in intimate contact with the water, then it resurfaces, having been subjected to dissolution.
- Chemicals present in the dispersant formulation may remain with the oil and alter the oil-water interfacial characteristics. For example it is observed that oil slicks which have been unsuccessfully dispersed "look different" in that there is a colour change and their recoalescence tendencies with rising oil drops are different, coalescence taking longer. Such behaviour is consistent with accumulation at the oil-water interface of either viscous (possibly wax or asphaltene) components of the oil or surfactant from the dispersant.
- Photolysis may result in stabilization of water-in-oil emulsions (mousses).

An experimental program described in this report was thus undertaken to elucidate this issue and to obtain more reliable data. The program involved the testing of three oils and three dispersants in laboratory systems. Some preliminary work was undertaken to determine the best test system for these purposes. As part of the study, oil was analysed in detail by GC during repeated dispersion to detect chemical changes, and physical-chemical properties were measured.

A parallel effort involved development of a simple mathematical model of the multi-hit dispersion process.

## 2. THEORETICAL.

In the proceedings of a 1982 ASTM symposium on dispersants, Mackay et. al. (1984) developed a simple mathematical model of chemical dispersion which we apply in this study. The basic equation is

$$F = 1 - \exp(KE.KO.KD.R)$$

where
F is fraction of oil dispersed
KE is a constant determined by the turbulence
KO is a constant determined by the oil
KD is a constant determined by the dispersant
R is the effective dispersant to oil ratio.

Values of F are obtained experimentally at various selected values of R. Two constants must be arbitrarily assigned a value of unity and a third allowed to adopt an appropriate value as determined by experiment. In this case we assign KO and KD as unity for Norman Wells crude oil and Corexit 9527. For a specific apparatus at given values of R and the resulting F, KE can be deduced. It is postulated to be constant for all tests thereafter provided that the same level of turbulence is maintained.

The equation assumes (wrongly) that there is no interaction between oil type and dispersant type. When this occurs, the product (KO.KD) can be determined by experiment but it will not necessarily equal the product of KO obtained from tests with other dispersants and KD obtained from tests with other oils.

In a "N" multi-hit approach R the dosage is reduced to R/N individually, causing a reduction in F individually to f. The fraction of oil remaining after a test dispersion is (1-f) thus after N dispersions it would be (1-f) raised to the power N provided that f remains constant.

The simplest "first order" model is then that

$$(1-f) = \exp(-KE.KO.KD.R/N)$$

$$\text{or } (1-f)^N = [\exp(-KE.KO.KD.R/N)]^N$$

$$= \exp(-KE.KO.KD.R)$$

$$= 1-F$$

where F is the one hit dispersion fraction. For example, if the group (KE.KO.KD) were to have a value of 10 then one hit application at a R of 0.05 or 1/20 would give F of 0.39. If a two hit approach is used (N=2), R/N is 0.025 and the first hit would give dispersion of 0.22 leaving 0.78 undispersed. The second hit would disperse 0.22 of 0.78 i.e. 0.17, giving a total of 0.39 as before.

This model can be used as a hypothesis to "test" the data. If there is significant departure from the predictions, it can be attributed to a change in KO as a result of exposure to evaporation, dissolution or chemicals in the dispersant.

To enhance the display of data it is desirable to present these equations graphically. The form of the graph suggested by the equation is a plot of log (1-F) or log (1-f) versus R or r where f is the total fraction dispersed following application of a total dispersant to oil ratio of r. If the line from the origin

(corresponding to F or f of zero and R or r of zero) through the single hit (F, R) point coincides with that through the multi-hit (f, r) points then there is no significant difference. The slope is -2.303 KE.KO.KD in both cases. If the multi-hit line (or points) lies above the single hit line then multi-hit application is less effective (smaller slope) and vice-versa. This is illustrated in Figure 2.1.

In a recent study of the mechanism of chemical dispersion Mackay et. al. (1985) suggested that the relationship between amount of oil dispersed and volume of dispersant applied may be linear (i.e. each volume of dispersant causes dispersion of say 40 volumes of oil) provided that the slick is thicker than some critical value. This model would have the algebraic form

$$F = XR \text{ or } f = Xr$$

where X is a performance factor of say 40. On Figure 2.1 such an equation would approximate the first order line at low values of F or R, then it would rapidly curve downwards reaching F of 1.0 or log (1-F) of -infinity when R equals 1/X. In that study it was also suggested that a more complex linear-then-first-order relationship may apply. This would correspond to a curved then linear relationship on Figure 2.1.

For the purposes of this study it is not necessary to have information as to the "route" to the final effectiveness. All that is required is information about the one - and multi-hit effectiveness at the same dose. We thus use the first order model to illustrate the data.

# 3. EXPERIMENTAL.

## 3.1 Materials

The oils used and their properties are described in Table 3.1. The dispersants were Corexit 9527, Corexit 9550 and BP MA700, kindly supplied by the manufacturers (Exxon and BP).

All tests were done using synthetic salt water containing 30 g/L of sodium chloride in tap water.

## 3.2 Analyses

Dispersed oil concentrations were measured by visible spectrophotometry using a Spectronic 20 Spectrophotometer (Bausch & Lomb) at 540 nm with dichloromethane as solvent.

GC was done using a Hewlett-Packard 5700A Gas Chromatograph with operating conditions as follows: Temp 1 = 50 deg.C; Time 1 = 8 min; Rate = 5 deg.C/min; Temp 2 = 230 deg.C; Time 2 = 32 min; Injection port temp = 250 C and detector temp = 300 deg.C.

Densities and viscosities were measured at room temperature using standard hydrometers and viscometers.

## 3.3 Equipment and Procedure

The MNS system was essentially that described by Mackay and Szeto (1981) and was used in the standard manner with 10 mL of oil at a pressure drop over a 2 cm diameter orifice plate of 20 cm of water at 15 deg.C.

The hoop apparatus is shown in Figure 3.1 It consists of a 37 cm diameter by 30 cm deep open plastic tank, containing a 20 cm depth (0.024 m3) of 30 g/L salt water at 15 deg.C. An oscillating ring of diameter 31 cm acted as a wave generator. It was made from 0.6 cm diameter tubing bent into the form of a hoop. This hoop was just immersed in the water and could be raised and lowered at a rate of 200 vertical strokes per minute driven by a 12 volt Chrysler windshield wiper motor powered by a 12 volt car battery. A sampling tube was immersed at a depth of 8 cm below the water surface.

The required volume of oil (usually 100 cm3) was poured on to the surface of water. After the oil had risen to the water surface, the hoop was oscillated. Dispersant was delivered on to the oil surface by a hand operated garden spray and a timer was started. The amount of the dispersant delivered was determined by weighing the spray assembly with an analytical balance before and after spraying. Samples were collected periodically. A sample was allowed to drain into a beaker for 15 seconds. Then about 50 cm3 of sample was collected in a sampling bottle. The contents of the beaker were poured back at the side of the tank so that the oil surface was not disturbed. For one hit tests, the experimental time was about 92 minutes. For multi-hit test, the dispersant was sprayed at time zero, 31 minutes and 62 minutes. The duration of the experiment was about 92 minutes.

The Double Tube or "Bobra" system used was that described by Mackay et al. (1984) at the 1984 AMOP conference.

## 4. RESULTS AND DISCUSSION.

### 4.1 System selection tests.

Some exploratory tests with the MNS system showed that it was unsuitable for the present purposes. After the containment ring is removed, the oil spreads rapidly over the water surface and is partially dispersed. It is then impossible to add more dispersant to the oil in a reproducible manner. Further, the small quantity of oil used (10 mL) makes sampling for physical chemical property determination very difficult. The hoop system proved to be much more suitable because the oil tends to be confined reproducibly in a relatively small area on the water surface and repeated dispersant application is easily achieved.

The Double Tube or Bobra system is particularly advantageous for observing the oil slick behaviour during dispersion but it suffers from the problem of having a small oil volume of only a few mL. Some limited testing was done with it, principally to observe how the slick properties change with time after dispersion.

It was concluded that the principal experimental effort should be undertaken on the hoop system and only the results from this system are reported.

4.2 Hoop system results.

Figures 4.1 to 4.10 show the percent dispersed as a function of time for various combinations of oil and dispersant. In each figure, one curve represents a single dosage of dispersant whereas the other represents "multi-hit" dosage. Ideally the total amount of dispersant should be equal in both cases, however the present spray system does not give a reproducible dosage. Hence the comparison of the two curves can only be relative. Figures 4.11 to 4.20 give the same data in semi logarithmic plots. The results are also given in Tables 4.1 to 4.3.

The general shape of the concentration versus times curve is that immediately after the addition of dispersant, the concentration rises sharply which indicates rapid initial dispersion. The slope of the curve then decreases, dispersion reaches a maximum, tends to drop as some resurfacing occurs, and then stabilizes.

It should be noted that these experimental results depend on factors such as temperature, the energy input to the system, the oil and dispersant interaction, the oil droplet size and their distribution in the system. Here, the temperature is a minor factor since it varies by only 2 deg.C. The energy input to the system depends primarily on the voltage from the battery. Higher energy input to the system gives higher dispersion. The oil and dispersant mixing and the resultant oil droplet size apparently depend primarily on the properties of the oil and dispersant. If the mixing is slow, the slope of the rising curve is low and a longer time is taken for the curve to reach its maximum. If the oil droplets are large, they tend to resurface quite rapidly. Frequently it was observed that the oil droplets would coalesce to form larger droplets and rise up to the slick. The distribution of the oil droplet diameter apparently depends on the turbulence of the system. This has also been reported in more detail by Lewis et. al. (1985). The non-uniform distribution shows up in the scatter of the data and in some dispersion fractions F greater than 1.0 or 100% which is the result of an atypically dense cloud of oil droplets or very large droplets being collected in the sample.

The results are best discussed by examining the plots of log (1-F) versus R in Figures 4.11 to 4.20. In doing so it should be noted that the error in percent dispersed is believed to be plus or minus a factor of 1.3 in F at low values of F or a similar factor in (1-F) at high values of F. This corresponds approximately to error bars of plus or minus 1 cm on these figures, thus only points distant by 2 cm are believed to be significantly different.

Applying this criterion, the following systems show no significant difference between multihit and one hit dispersion in the following six cases:

Beaufort Sea Crude - Corexit 9527
Beaufort Sea Crude - BP MA 700
Norman Wells Crude - BP MA 700
EPS Standard - Corexit 9527
EPS Standard - BP MA 700
EPS Standard + wax - Corexit 9527

In four cases one hit dispersion was inferior, namely

Beaufort Sea Crude - Corexit 9550

EPS Standard - Corexit 9550
Norman Wells Crude - Corexit 9527
Norman Wells Crude - Corexit 9550

In no case was multihit dispersion significantly better.

These results must be interpreted with caution because there is a lack of replication and the effects are not large compared to the errors. It appears that in general there is no significant difference in dispersion, but Corexit 9550 shows a consistent tendency to perform better when applied in one hit. It is suspected that the phenomenon being observed is essentially the extent of contacting and mixing between the oil and dispersant. The greater the amount of oil, i.e. greater thickness, the better is the mixing-contacting. With thin slicks which may only partially cover the surface, there is a greater tendency for dispersant to land on sheen or water or to penetrate the slick.

The behaviour of Corexit 9550 may be misleading because this dispersant is designed for use on viscous oils, but is applied here to relatively light oils.

During the test of the multi-hit of Corexit 9527 and Norman Wells crude oil, samples were collected at the oil surface for GC analyses. Figures 4.21 to 4.27 are the chromatograms which show the change in composition of Norman Wells crude oil. 30 minutes after the first dosage of Corexit 9527 to the oil, about 22% of the oil had evaporated, 30 minutes after the second dosage, about 24% of oil had evaporated and 30 minutes after the third dosage, about 26% of oil had evaporated. The corresponding dispersed oil showed similar chromatograms to the oil slick. There are apparently no significant changes in oil composition as shown by GC analysis.

Table 4.5 shows the viscosity and the density change of the oil slick before and after the experiment. As expected, the viscosity and density increased due to evaporation and dissolution of the volatile portion of the oil. The magnitude of the increase is not large.

To test the effect of oil composition, 5.6 mass percent wax was added to EPS Standard oil and the oil was dispersed with Corexit 9527. Figure 4.10 shows the percent dispersion vs time. The dispersion efficiency improved only slightly upon the addition of a large amount of dispersant. The oil slick chromatograms of the multi-hit and the single dosage experiments are similar.

## CONCLUSIONS AND RECOMMENDATIONS.

The single and multi-hit dispersion of three crude oils has been studied using three dispersants. A simple mathematical model has been devised to provide a hypothesis against which the experimental data can be tested. A convenient method of displaying this hypothesis or model graphically has been devised.

It is concluded that in general there is no significant consistent difference between single and multi-hit application for this test system for the oils and dispersants tested. This is consistent with the intuitive deduction that when the oil properties change relatively little between hits, there should be no significant difference between the two techniques.

It is believed that situations may occur (and are believed to be illustrated by the experimental results) in which multi-hit treatment is less effective. These situations include the formation of water-in-oil emulsion between hits, the rise in viscosity above 5000 mPa.s due to evaporation (or equivalently the rise in pour point to near ambient temperature), and the loss in efficiency that may be attributable to thinning of the oil slick and hence less intimate oil-dispersant contact. In the earlier work in which poor multi-hit dispersion occurred it seems likely that there was significant oil weathering resulting in a marked increase in viscosity which retarded oil-dispersant mixing during the repeat application. It is frequently observed that the initial dispersion causes a large increase in slick surface area, thus it becomes increasingly difficult to treat all that area.

On the basis of this and other work the authors conclude (with an element of subjective judgement) that the preferred strategy is to apply dispersant in one hit as accurately as possible to the thick portions of the oil slick, ignoring the sheen which will probably disperse naturally. If there is insufficient dispersion, it may be advantageous to apply more dispersant to remaining thick patches. In most cases this multi-hit treatment is likely to be effective except when a significant change in oil properties occurs, or when the early dispersion results in significant thinning of the slick and hence less effective mixing and contacting when dispersant is subsequently added.

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Table 3.1 Properties of Oils at 23°C

| Oil | Density ($kg/m^3$) | Viscosity (mPa.s) |
|---|---|---|
| Beaufort Sea Crude | 870 | 62 |
| Norman Wells Crude | 841 | 52 |
| EPS Standard | 835 | 51 |
| 5.6 wt%wax-EPS Standard | 840 | 58 |

**Table 4.1 Dispersion Results (Beaufort Sea Crude)**

| Dispersant | R | $\Sigma r_i$ | Time (min) | Dispersion (%) |
|---|---|---|---|---|
| Corexit 9527 | 1/339 | | 100 | 68 |
| | | 1/618 | 31 | 17 |
| | | 1/359 | 62 | 83 |
| | | 1/267 | 100 | 84 |
| Corexit 9550 | 1/450 | | 100 | 95 |
| | | 1/566 | 31 | 45 |
| | | 1/354 | 62 | 81 |
| | | 1/243 | 100 | 93 |
| BP MA700 | 1/296 | | 100 | 74 |
| | | 1/857 | 31 | 15 |
| | | 1/290 | 62 | 76 |
| | | 1/196 | 100 | 99 |

**Table 4.2 Dispersion Results (Norman Wells Crude)**

| Dispersant | R | $\Sigma r_i$ | Time (min) | Dispersion (%) |
|---|---|---|---|---|
| Corexit 9527 | 1/234 | | 100 | 96 |
| | | 1/662 | 31 | 35 |
| | | 1/351 | 62 | 52 |
| | | 1/243 | 100 | 82 |
| Corexit 9550 | 1/146 | | 100 | 99 |
| | | 1/530 | 31 | 15 |
| | | 1/412 | 62 | 30 |
| | | 1/342 | 100 | 34 |
| BP MA700 | 1/288 | | 100 | 52 |
| | | 1/2515 | 31 | 16 |
| | | 1/221 | 62 | 51 |
| | | 1/159 | 100 | 90 |

**Table 4.3 Dispersion Results (EPS Standard and 5.6 wt % Wax-EPS Standard)**

**EPS Standard**

| Dispersant | R | $\Sigma r_i$ | Time (min) | Dispersion (%) |
|---|---|---|---|---|
| Corexit 9527 | 1/392 | | 100 | 23 |
| | | 1/587 | 32 | 34 |
| | | 1/297 | 64 | 44 |
| | | 1/218 | 100 | 45 |
| Corexit 9550 | 1/241 | | 100 | 99 |
| | | 1/261 | 38 | 48 |
| | | 1/198 | 70 | 91 |
| | | 1/172 | 100 | 93 |
| BP MA700 | 1/210 | | 100 | 74 |
| | | 1/482 | 31 | 25 |
| | | 1/299 | 62 | 52 |
| | | 1/236 | 100 | 95 |
| 5.6 wt% wax - EPS Standard | | | | |
| Corexit 9527 | 1/158 | | 100 | 10 |
| | | 1/124 | 31 | 8 |
| | | 1/76 | 62 | 10.5 |
| | | 1/50 | 100 | 12 |

**Table 4.4 The Dispersion Efficiency of Single and Multihit Dosage**

| | Corexit 9527 | Corexit 9550 | BP MA700 |
|---|---|---|---|
| Beaufort Sea Crude | M/L | L | M/L |
| Norman Wells Crude | M/L | L | M/L |
| EPS Standard | M/L | L | M/L |
| 5.6 wt% Wax-EPS Standard | M/L | - | - |

**Table 4.5. Viscosity and Density Measurements Before and After the Multihit Experiment at 23°C**

Oil: Norman Wells Crude
Dispersant: Corexit 9527

| Time (min) | Viscosity (mPa.s) 23°C | Density (kg/m$^3$) 23°C |
|---|---|---|
| 0 | 52 | 841 |
| 93 | 230 | 878 |

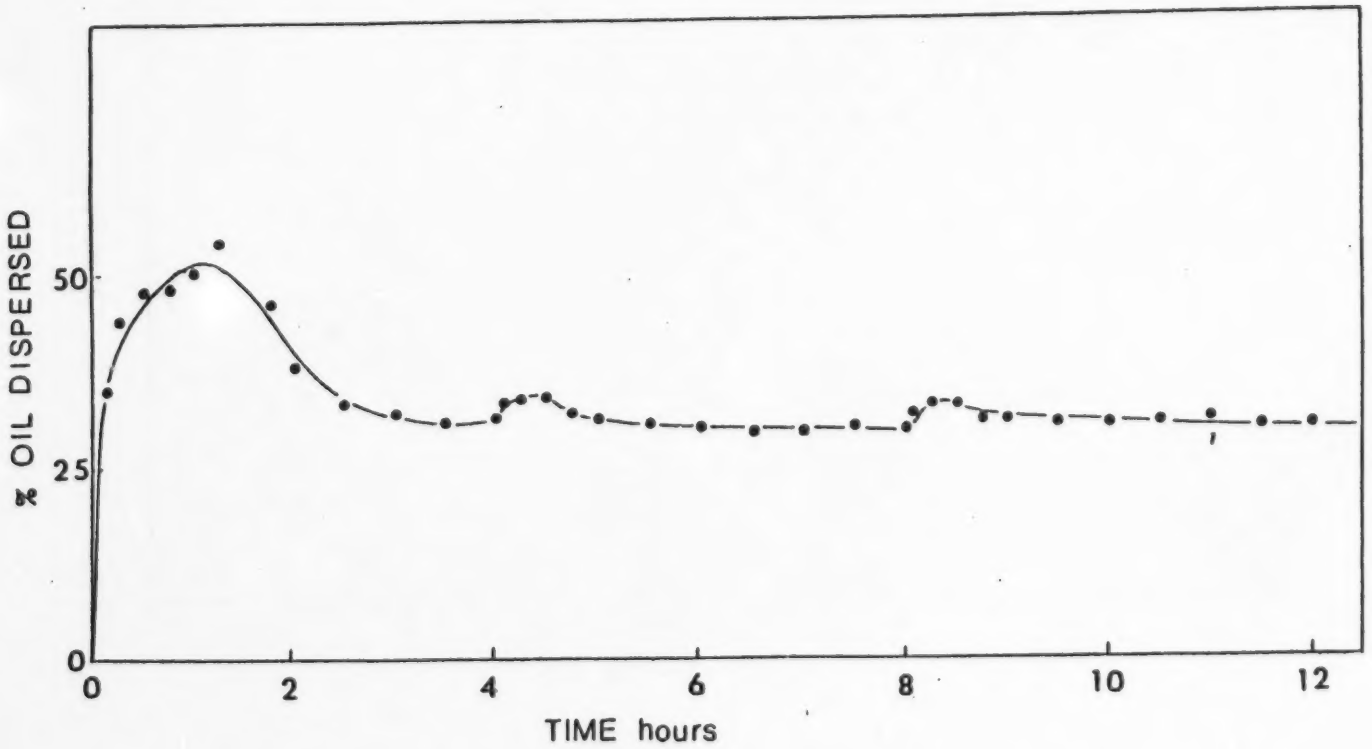
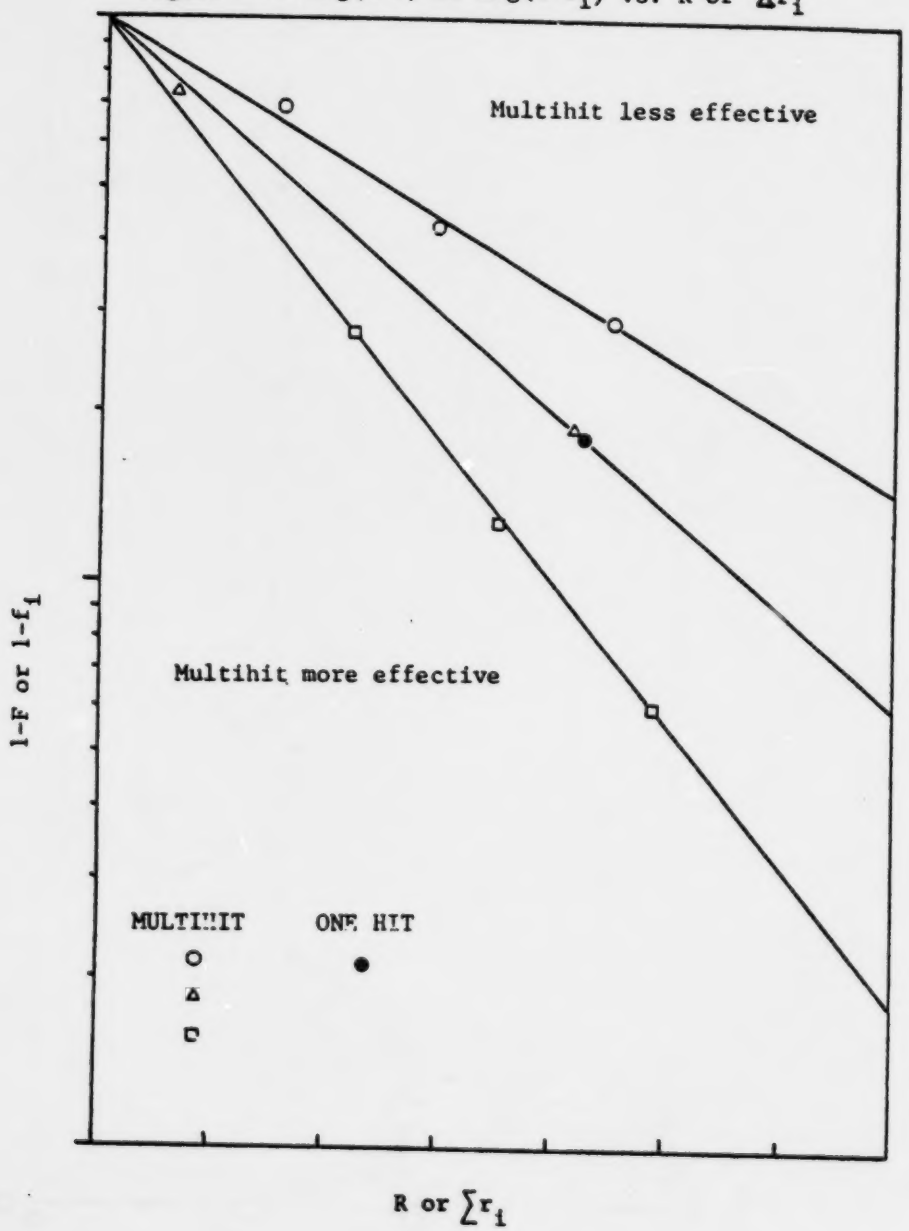



Figure 1.1: Effect of repeated application of dispersant D/O ratio 1:27, at 0, 4 and 8 hours, 0°C, ice absent.

Figure 2.1: Log(1-F) or Log($1-f_i$) vs. R or $\sum r_i$



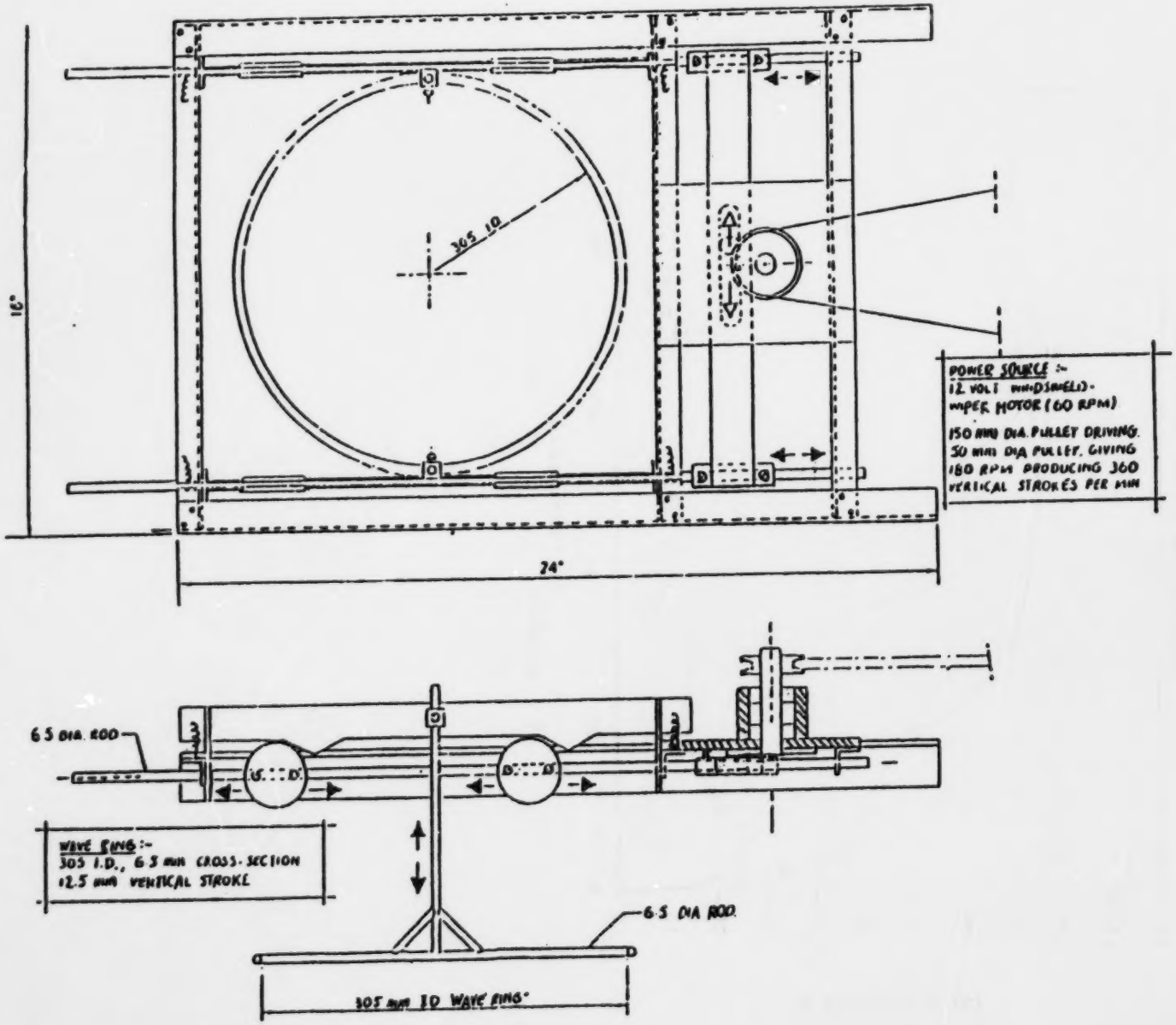
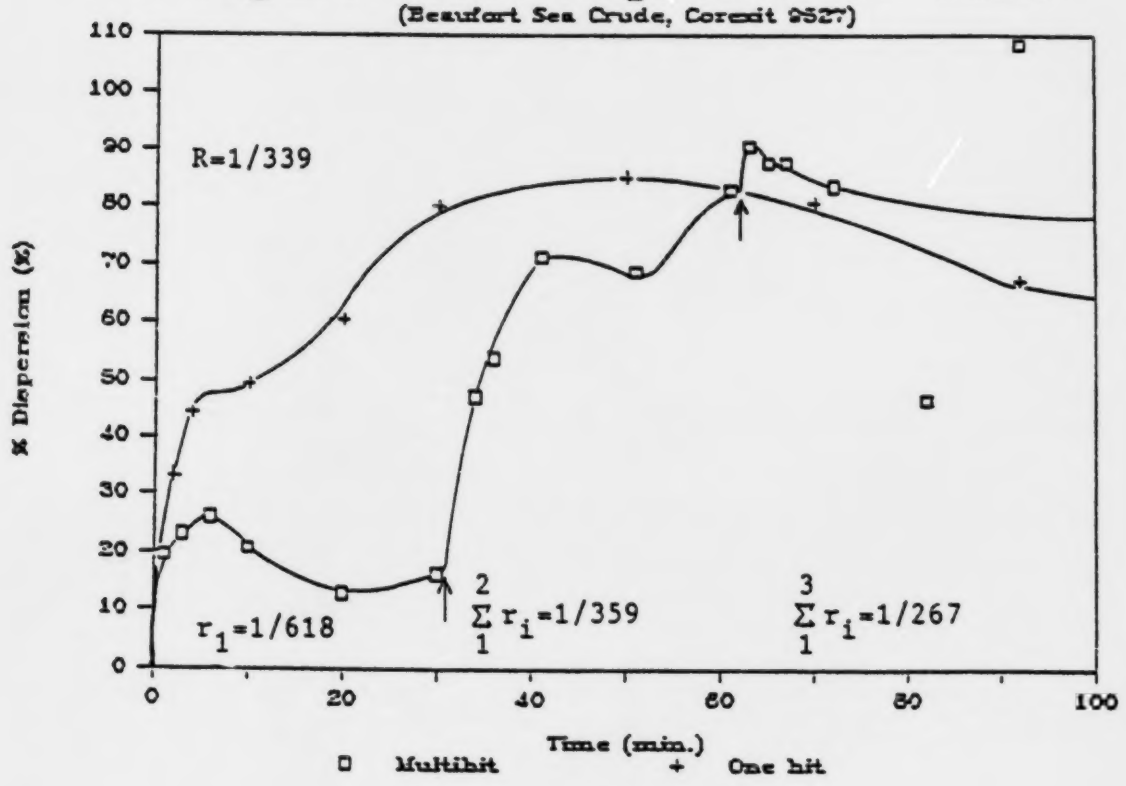

305 ID
16"
24"
POWER SOURCE :-
12 VOLT WINDSCREEN-WIPER MOTOR (60 RPM)
150 MM DIA PULLEY DRIVING 50 MM DIA PULLEY, GIVING 180 RPM PRODUCING 360 VERTICAL STROKES PER MIN
6.5 DIA. ROD
WAVE RING :-
305 I.D., 6.5 MM CROSS-SECTION
12.5 MM VERTICAL STROKE
6.5 DIA ROD
305 MM ID WAVE RING

Figure 3.1: The Hoop Apparatus

# Figure 4.1: % Dispersion vs. Time



Fi;e 4.2: % Dispersion vs. Time

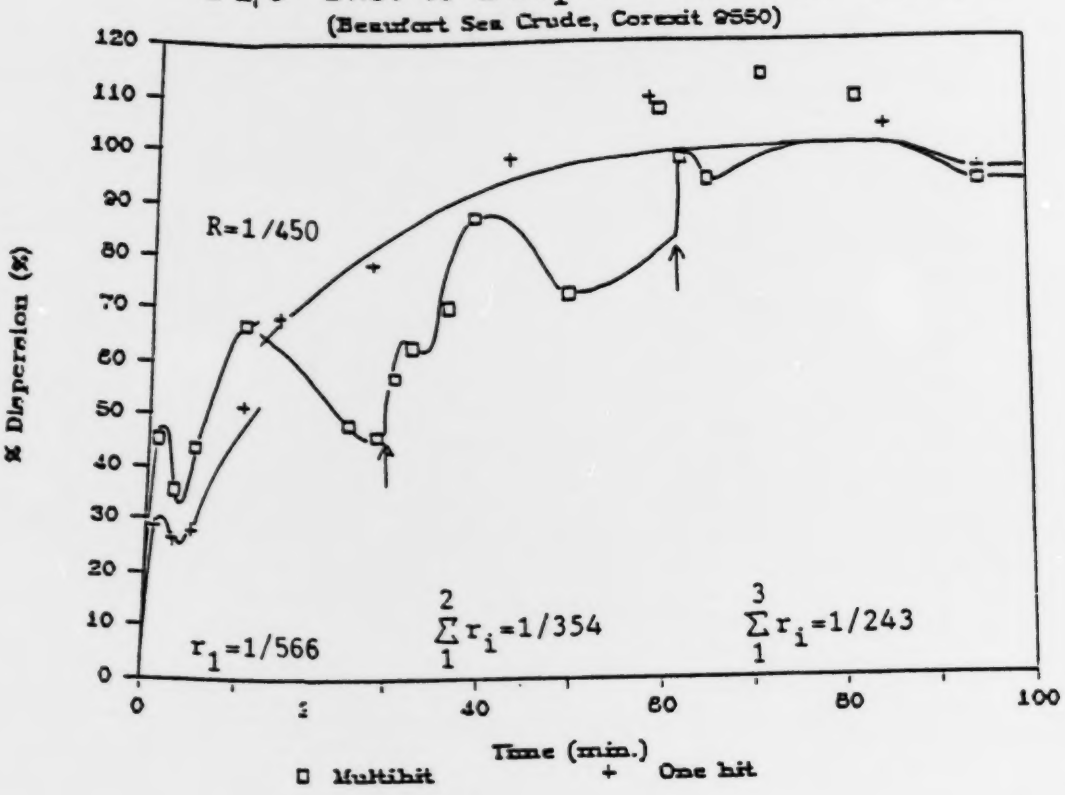


Figure 4.3: % Dispersion vs. Time

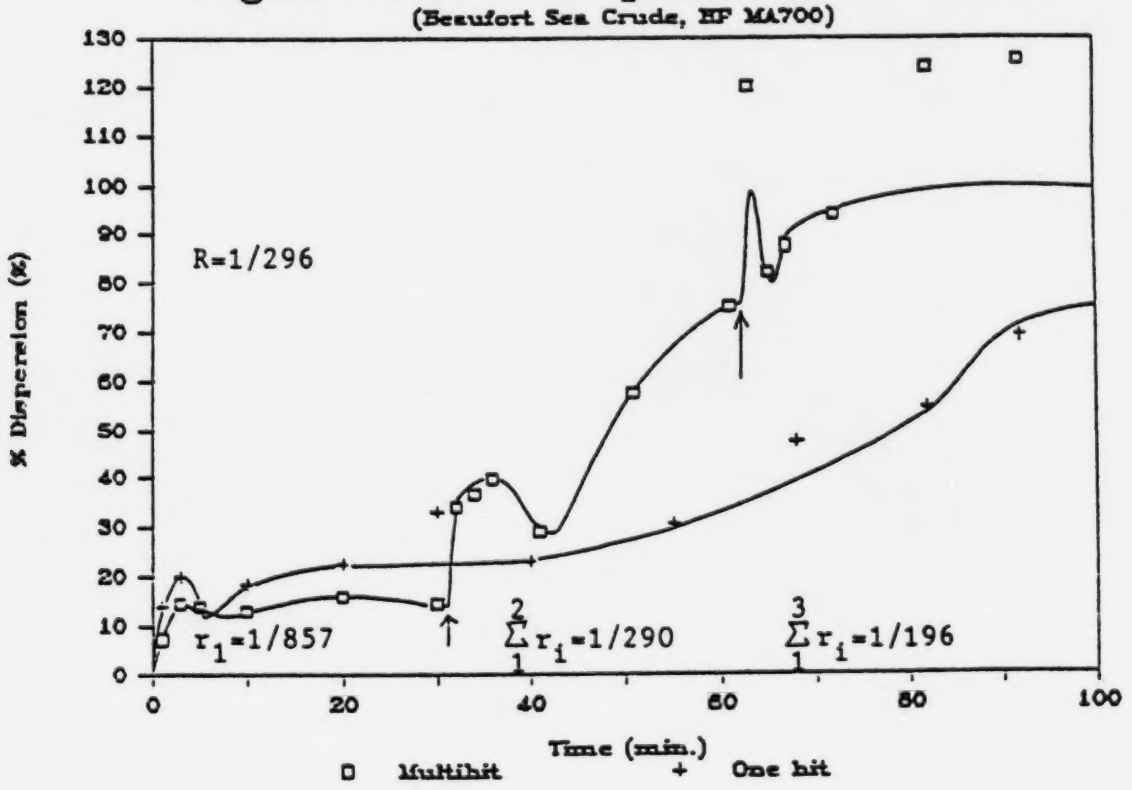
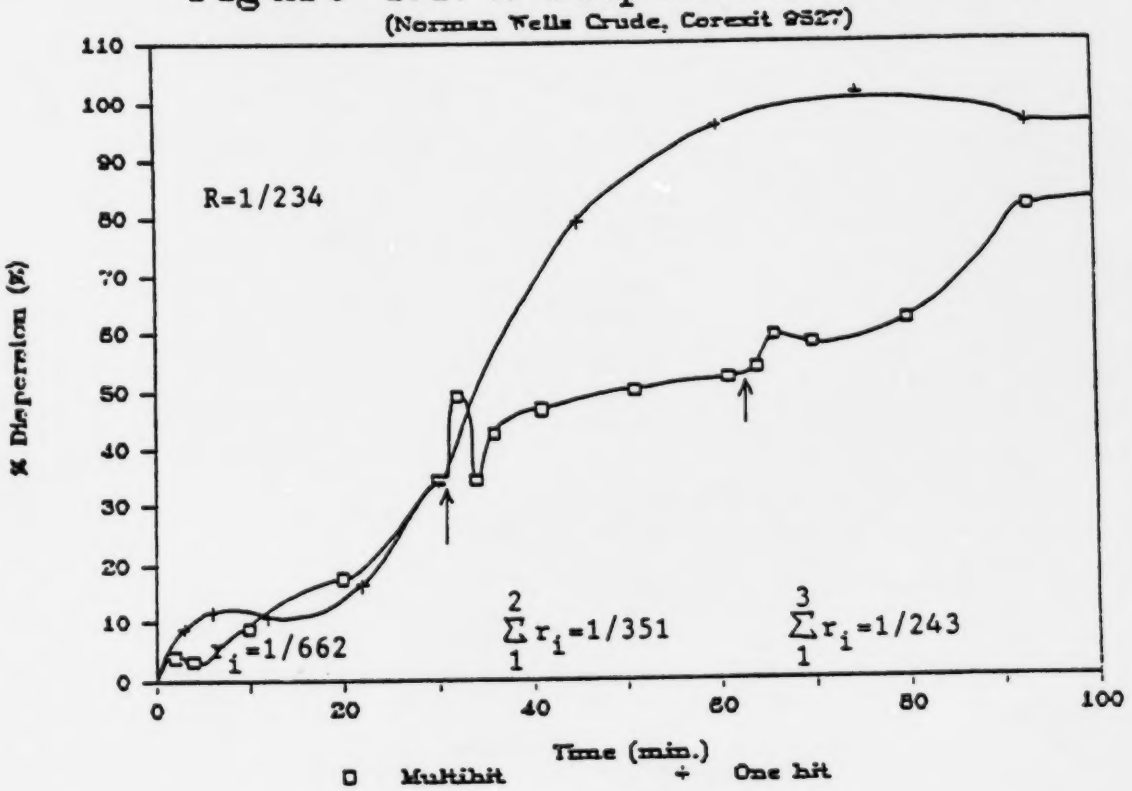


Figure 4.4: % Dispersion vs. Time



# Figure 4.5: % Dispersion vs. Time

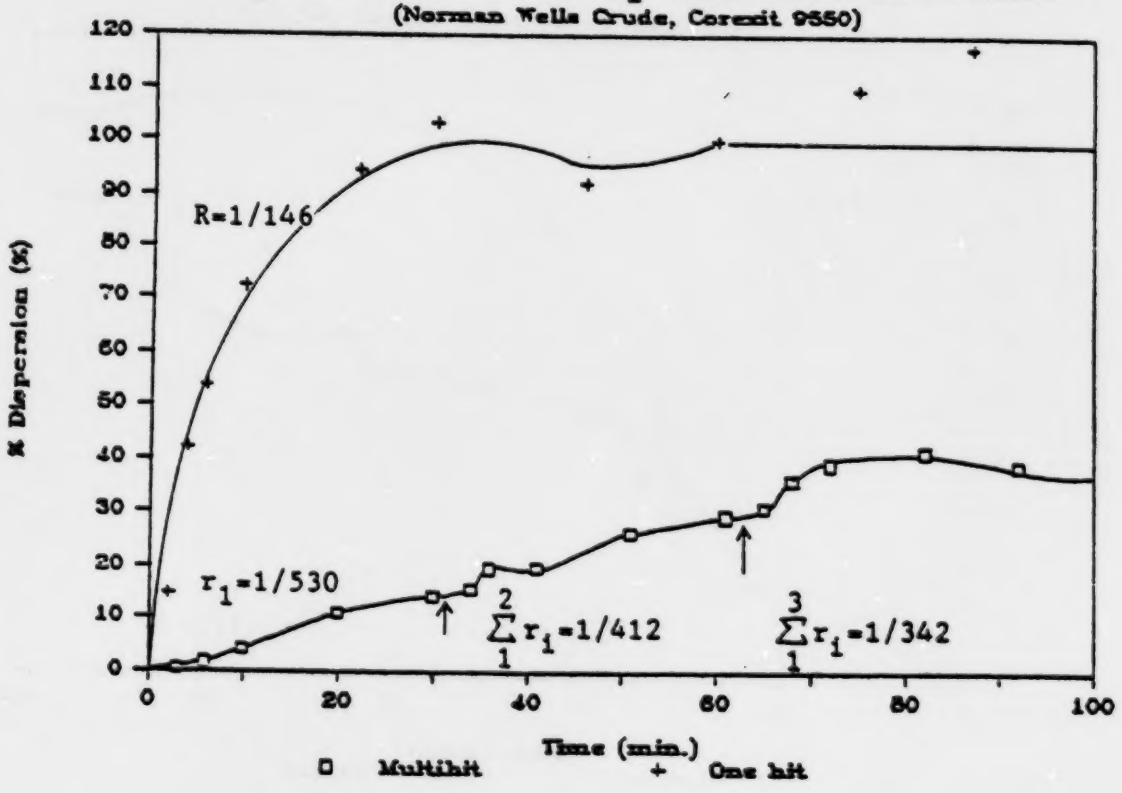
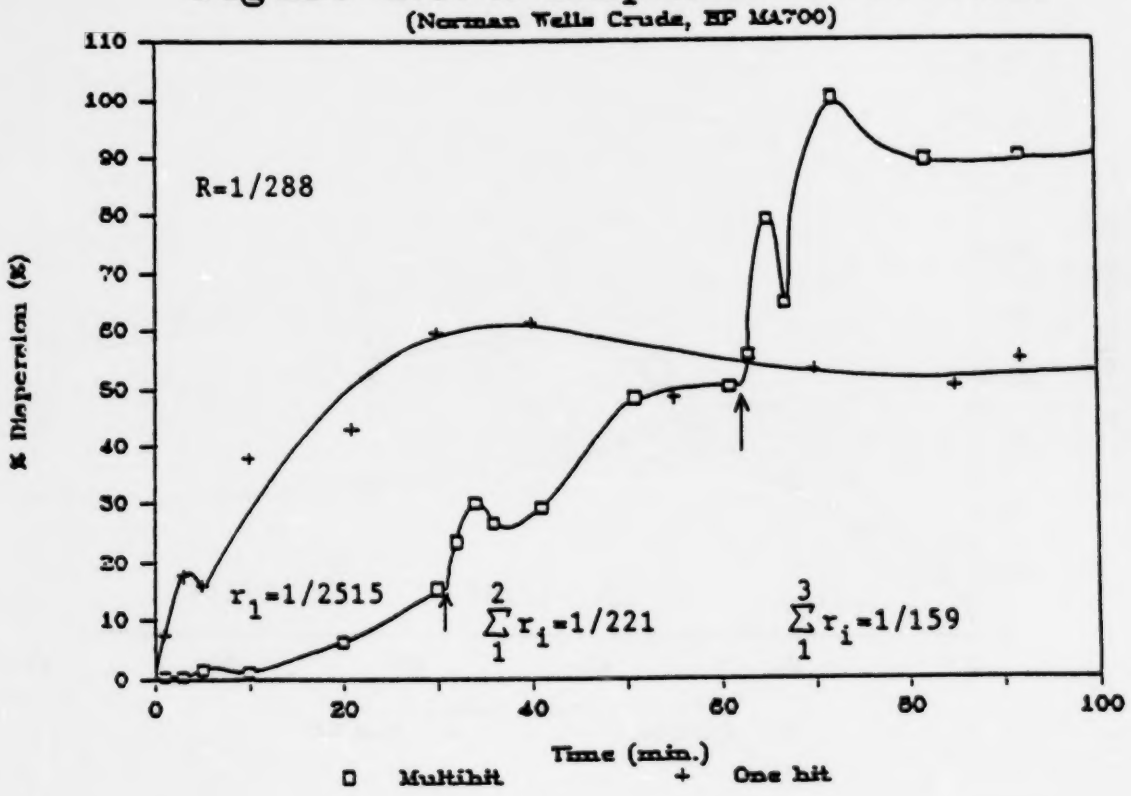


Figure 4.6: % Dispersion vs. Time



# Figure 4.7: % Dispersion vs. Time

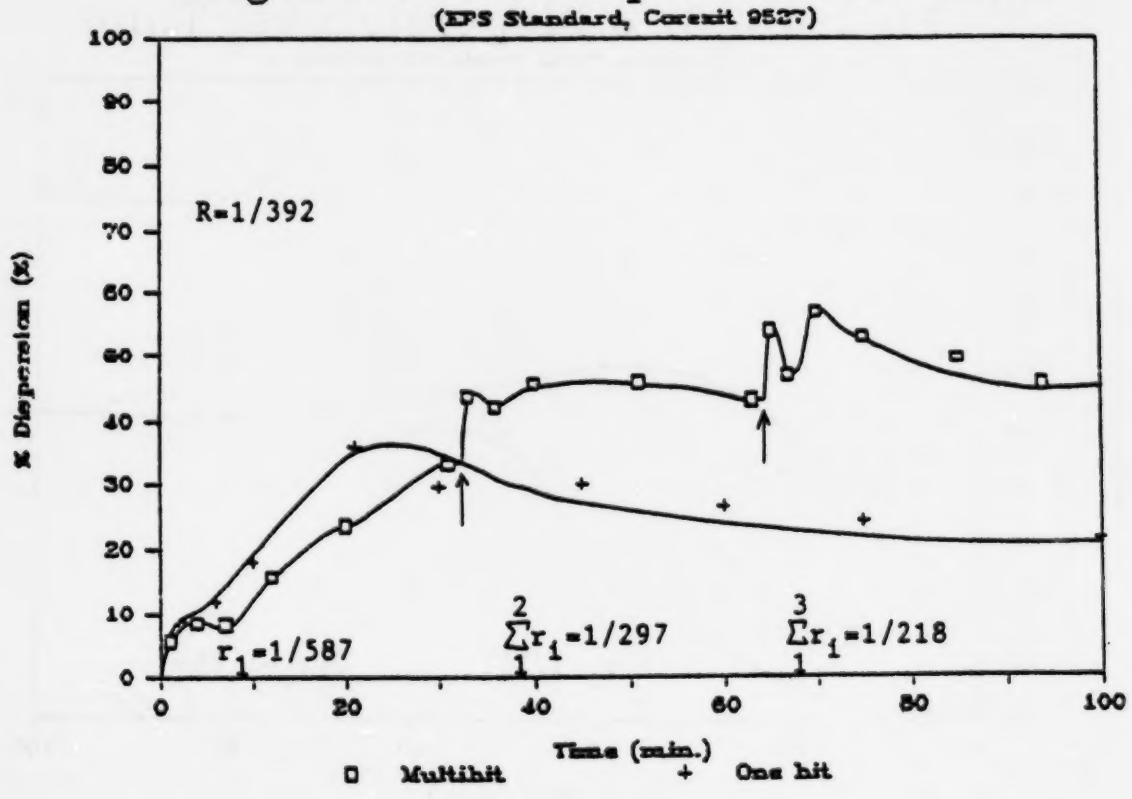
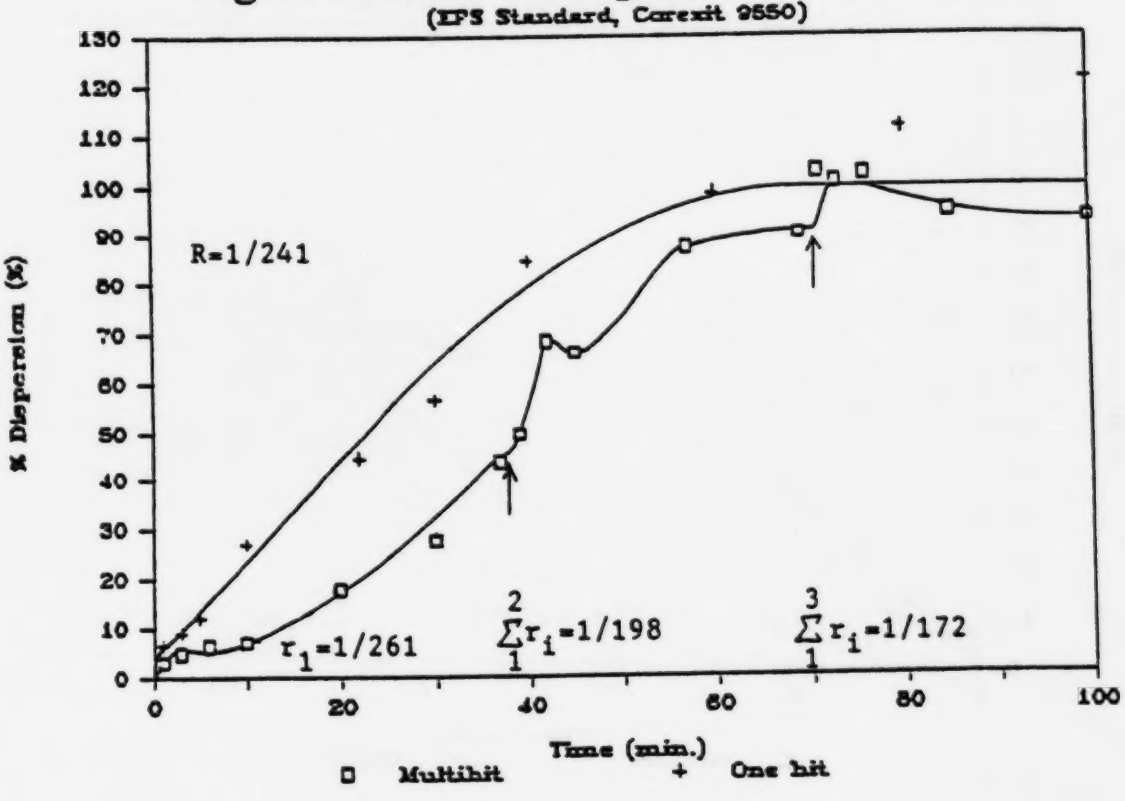


Figure 4.8: % Dispersion vs. Time



# Figure 4.9: % Dispersion vs. Time

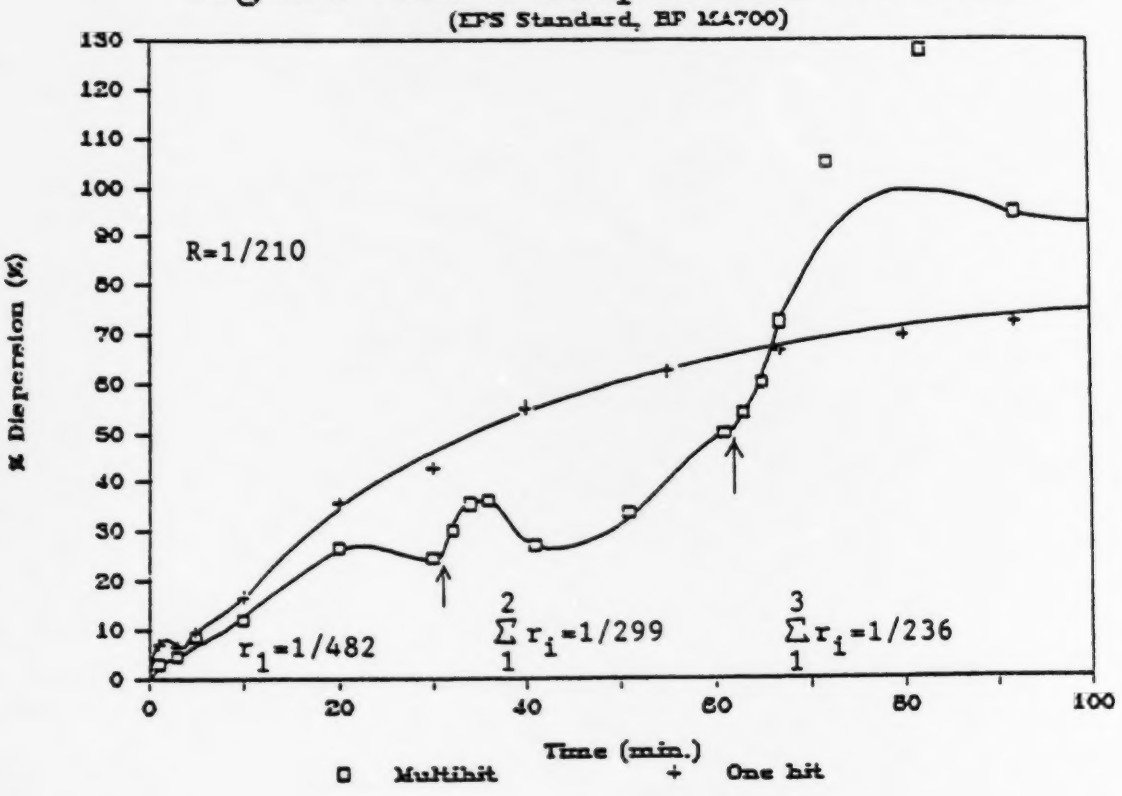


Figure 4.10: % Dispersion vs. Time

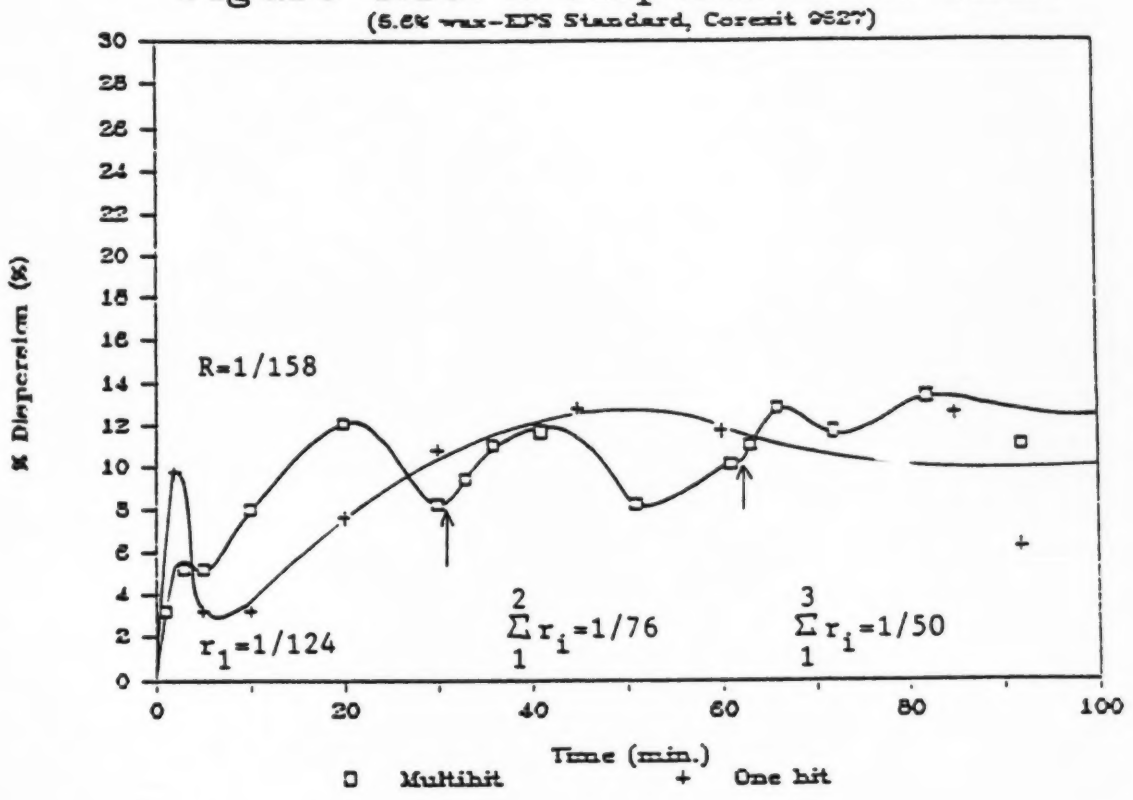


Figure 4.11: Log(1-F) or Log(1-$f_i$) vs. R or $\Sigma r_i$

(Beaufort Sea Crude, Corexit 9527)

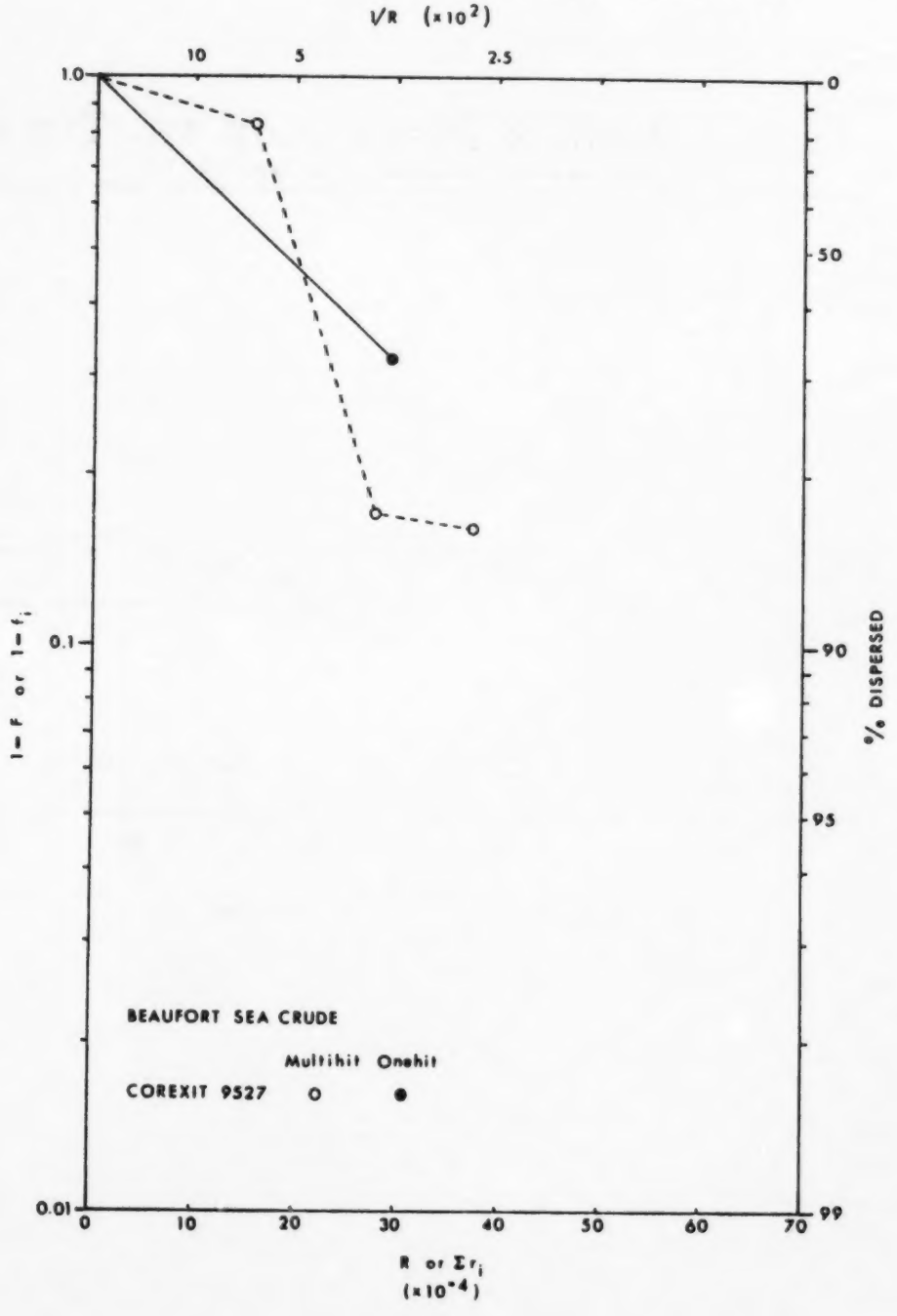


Figure 4.12: Log(1-F) or Log(1-$f_i$) vs. R or $\Sigma r_i$

(Beaufort Sea Crude, Corexit 9550)

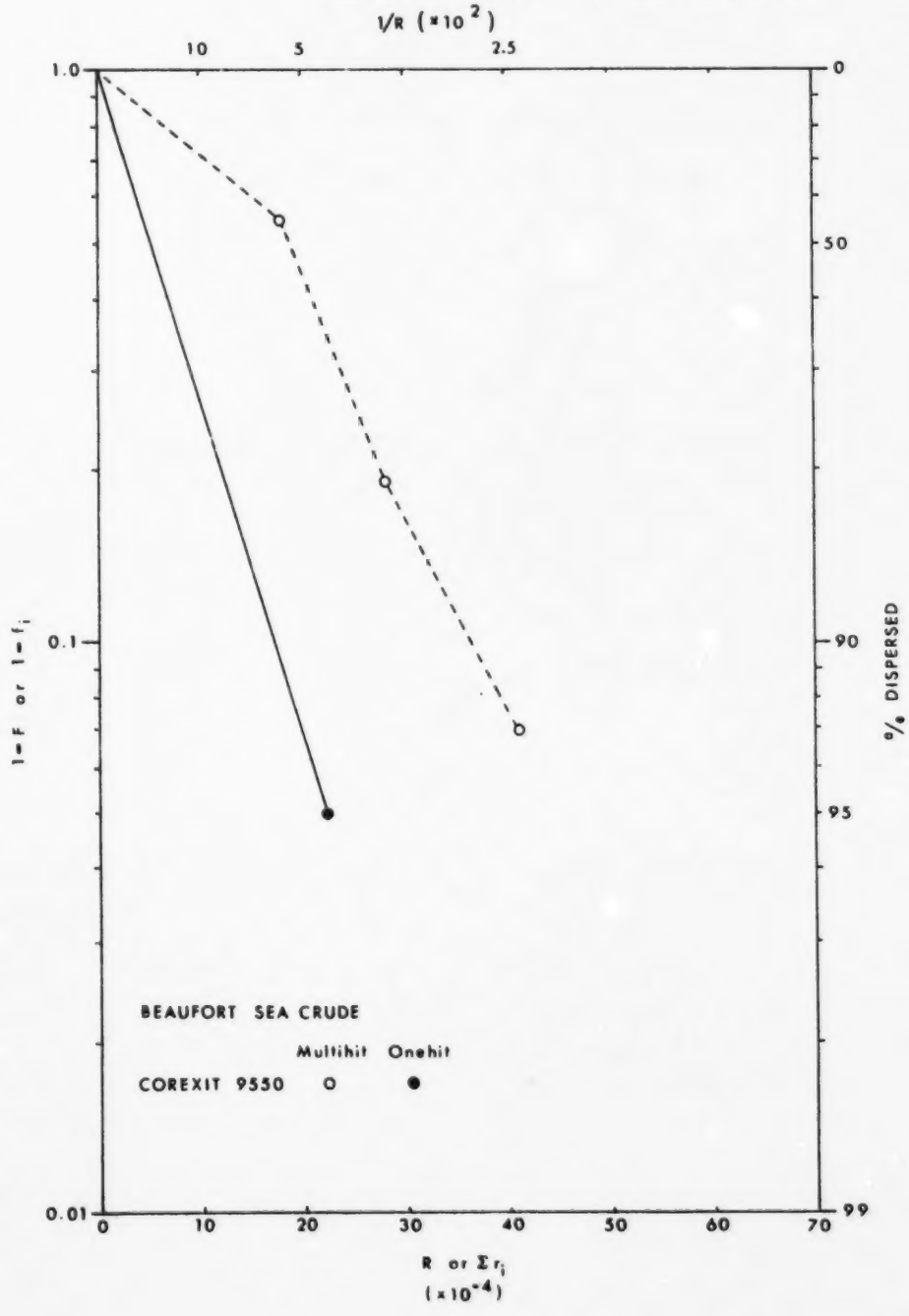


Figure 4.13: Log(1-F) or Log($1-f_i$) vs. R or $\Sigma r_i$

(Beaufort Sea Crude, BP MA700)

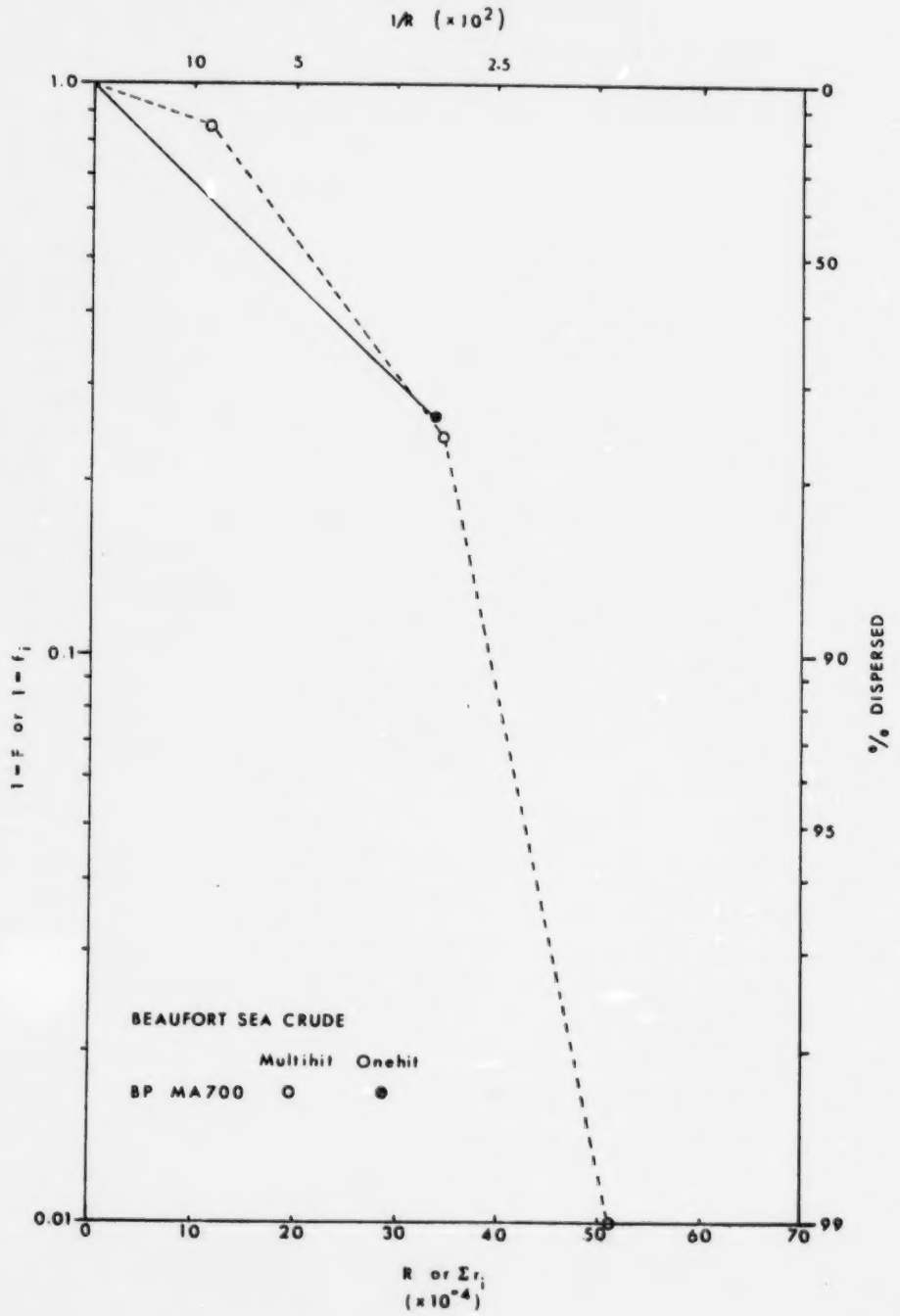


Figure 4.14: Log(1-F) or Log($1-f_i$) vs. R or $\Sigma r_i$

(Norman Wells Crude, Corexit 9527)

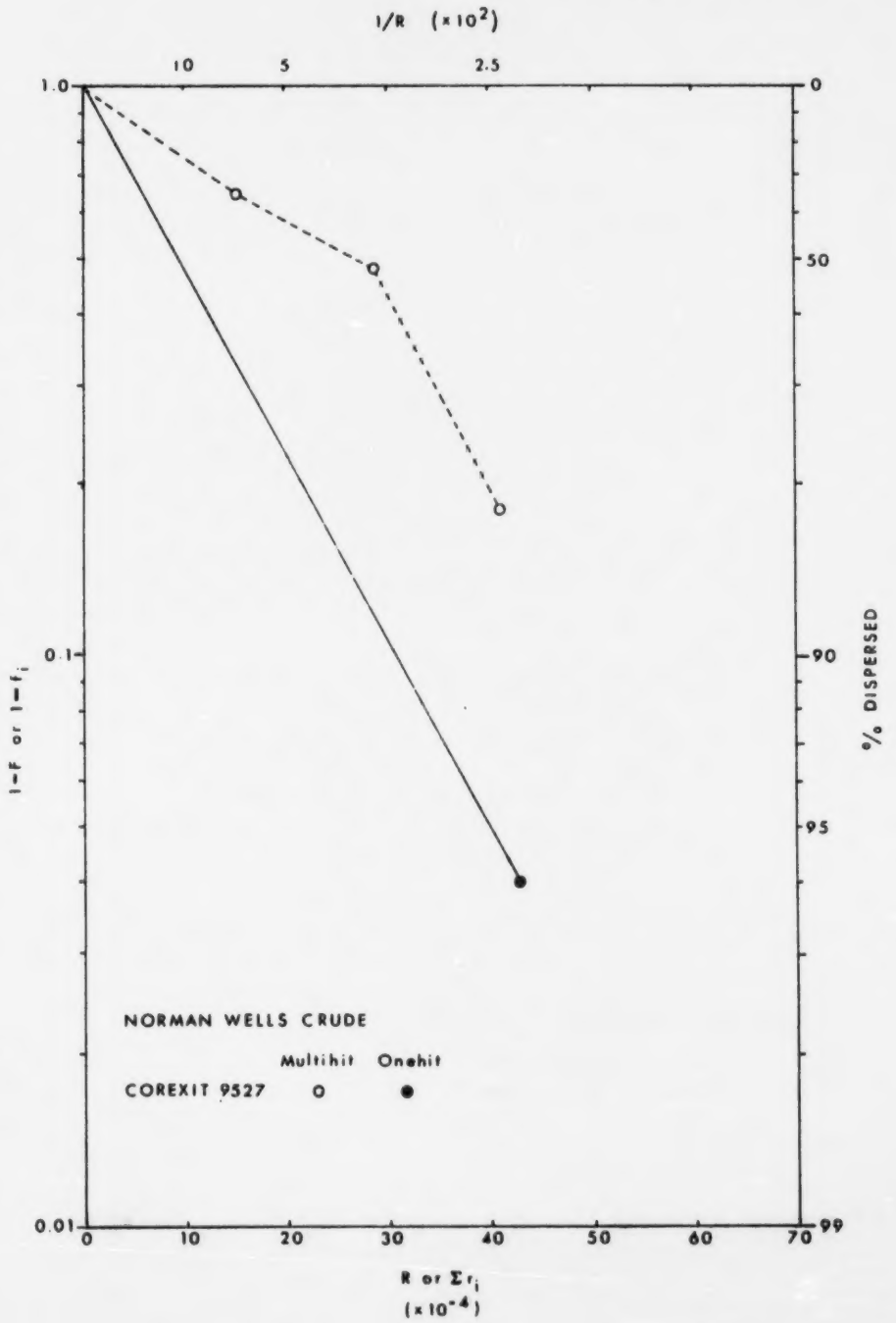


Figure 4.15: Log(1-F) or Log(1-$f_i$) vs. R or $\Sigma r_i$

(Norman Wells Crude, Corexit 9550)

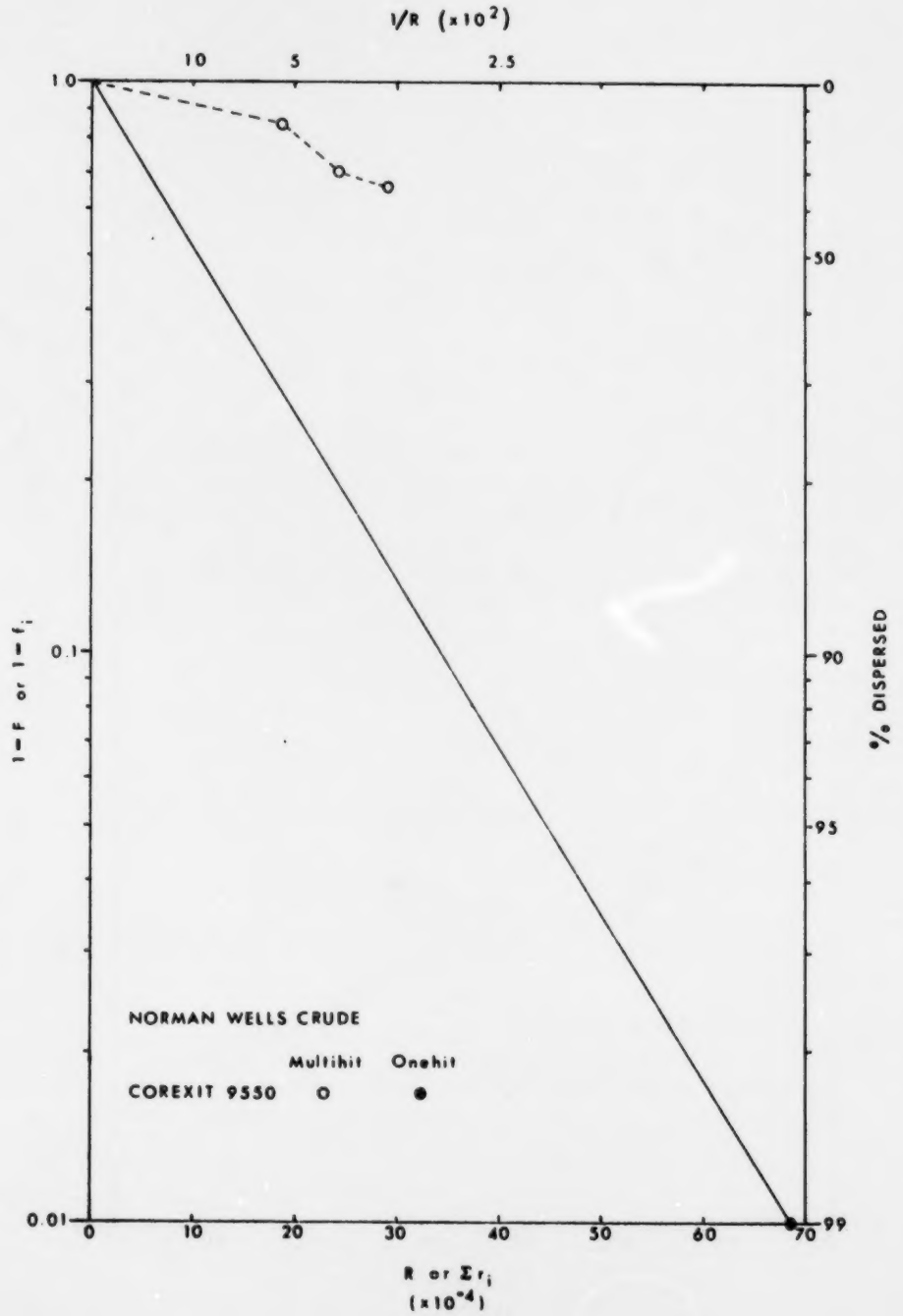


Figure 4.16: Log(1-F) or Log($1-f_i$) vs. R or $\Sigma r_i$

(Norman Wells Crude, BP MA700)

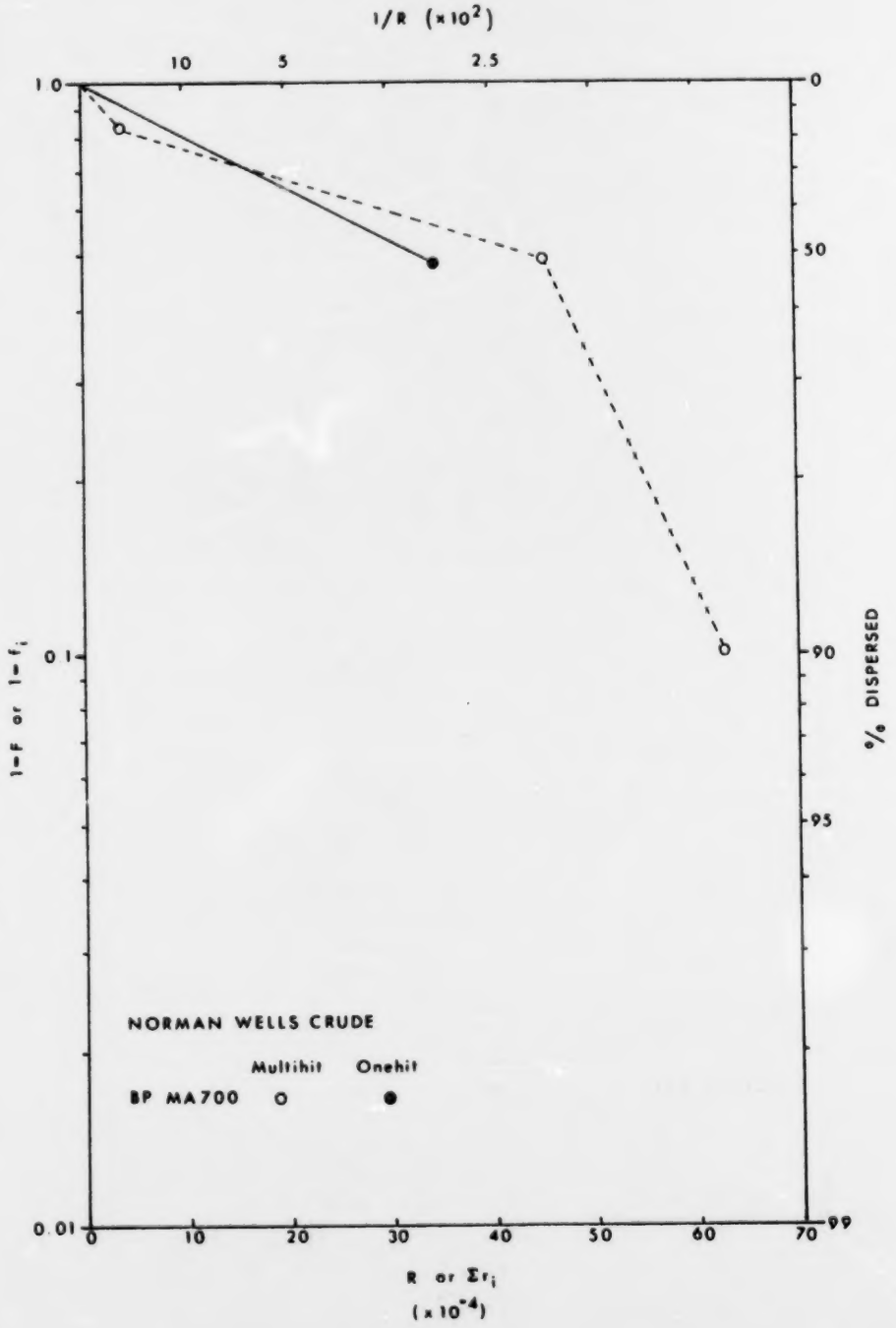


Figure 4.17: Log(1-F) or Log(1-$f_i$) vs. R or $\Sigma r_i$

(EPS Standard, Corexit 9527)

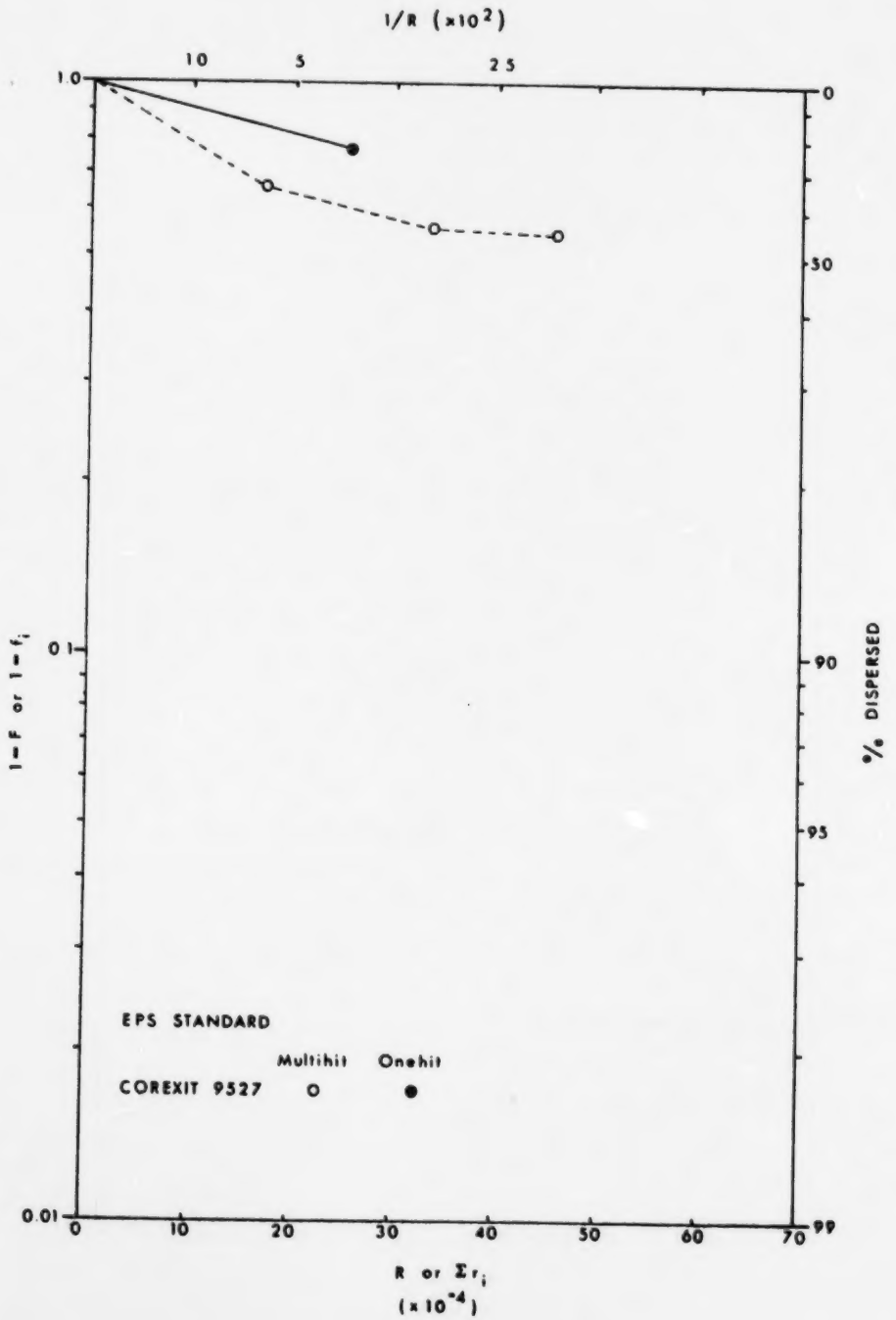


Figure 4.18: Log(1-F) or Log($1-f_i$) vs. R or $\Sigma r_i$

(EPS Standard, Corexit 9550)

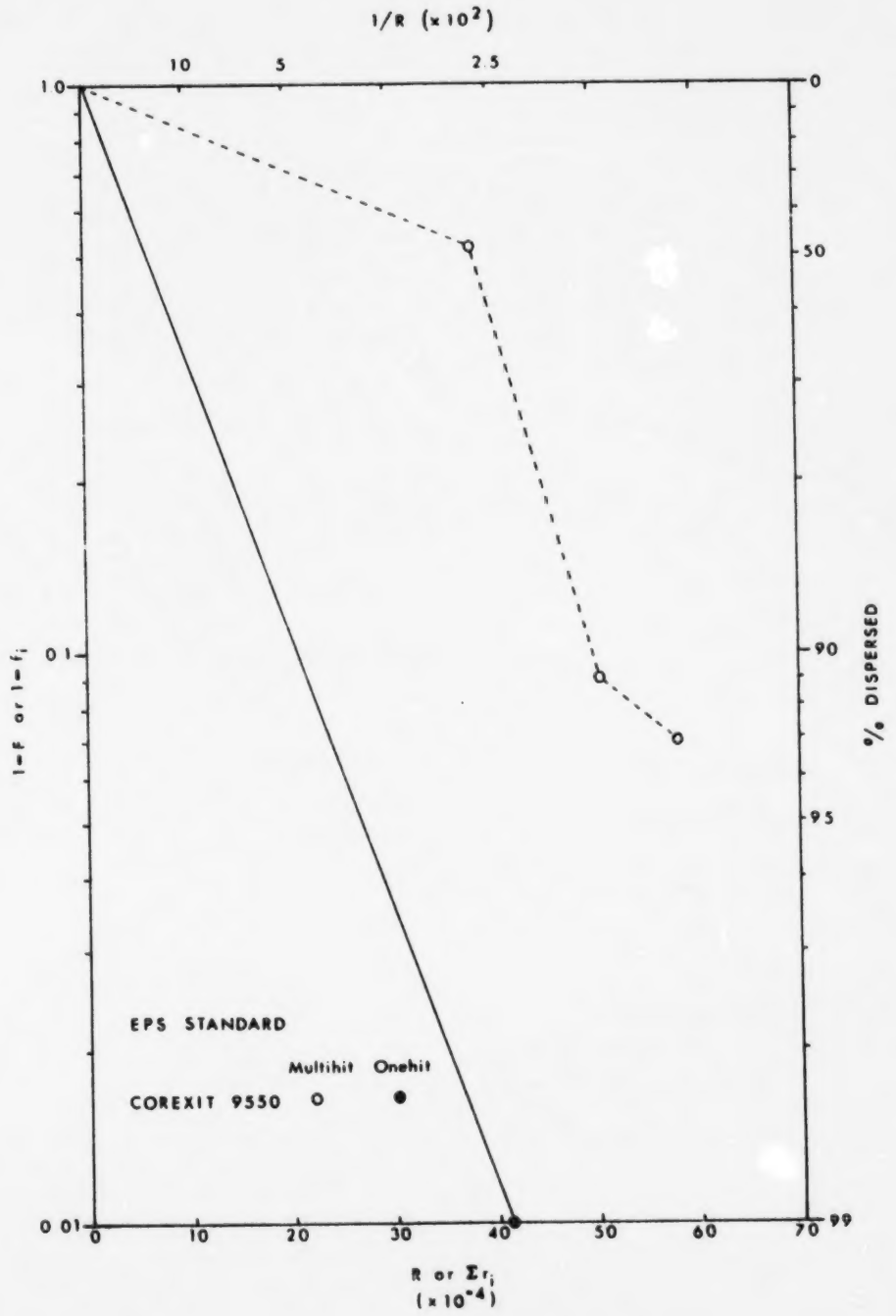


Figure 4.19: Log(1-F) or Log(1-$f_i$) vs. R or $\Sigma r_i$

(EPS Standard, BP MA700)

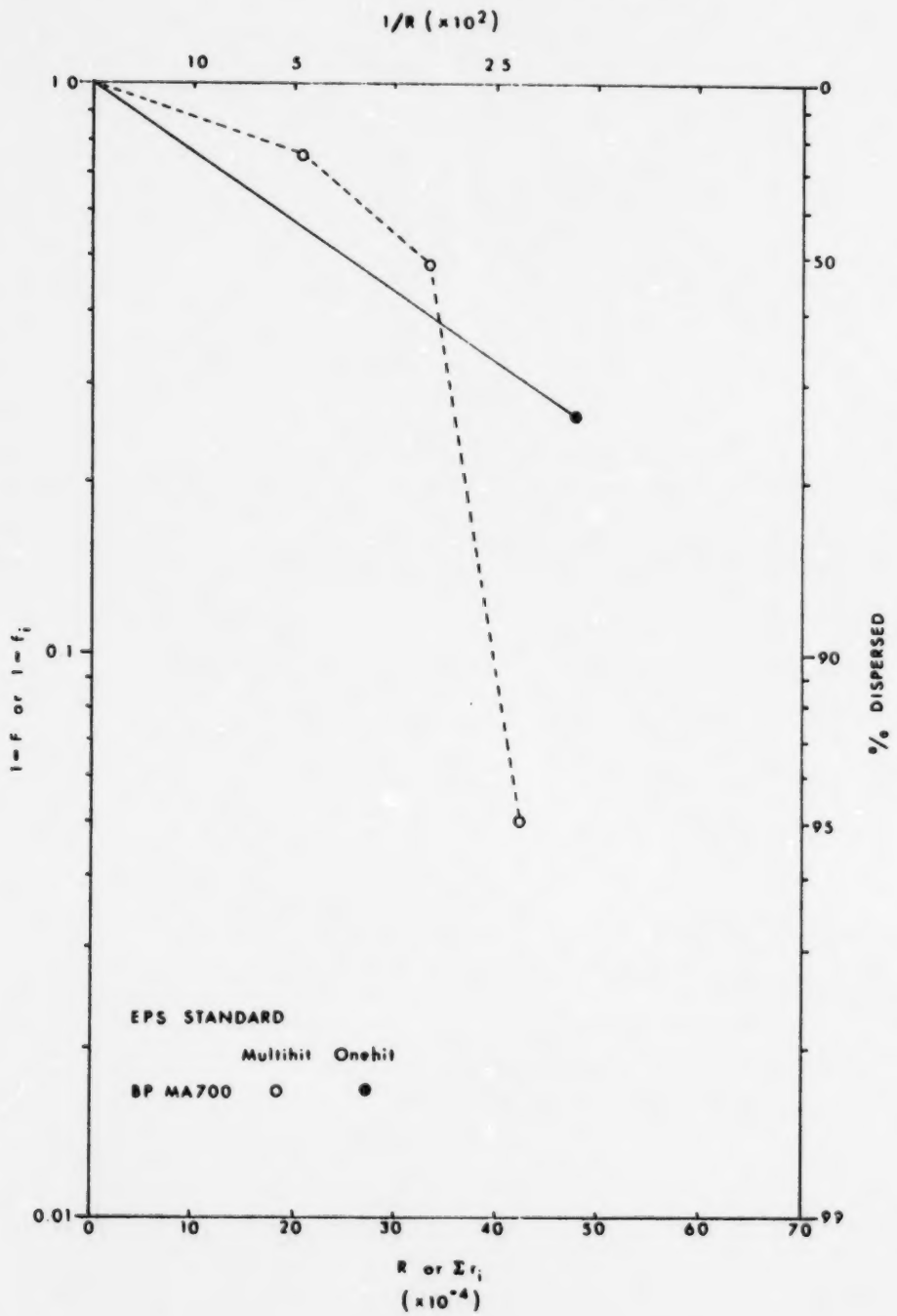
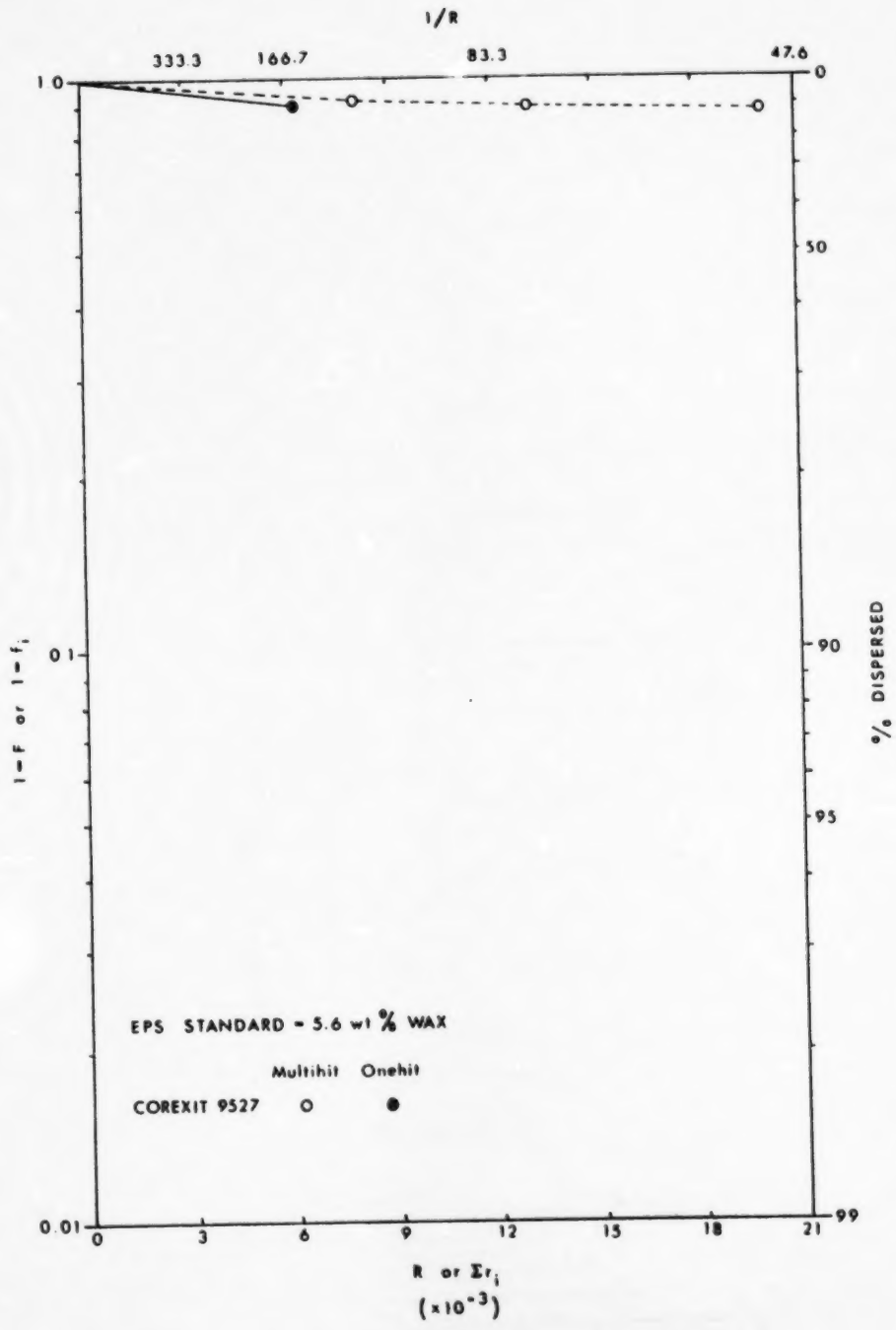


Figure 4.20: Log(1-F) or Log$(1-f_1)$ vs. R or $\Sigma r_i$

(EPS Standard-5.6 wt% wax, Corexit 9527)



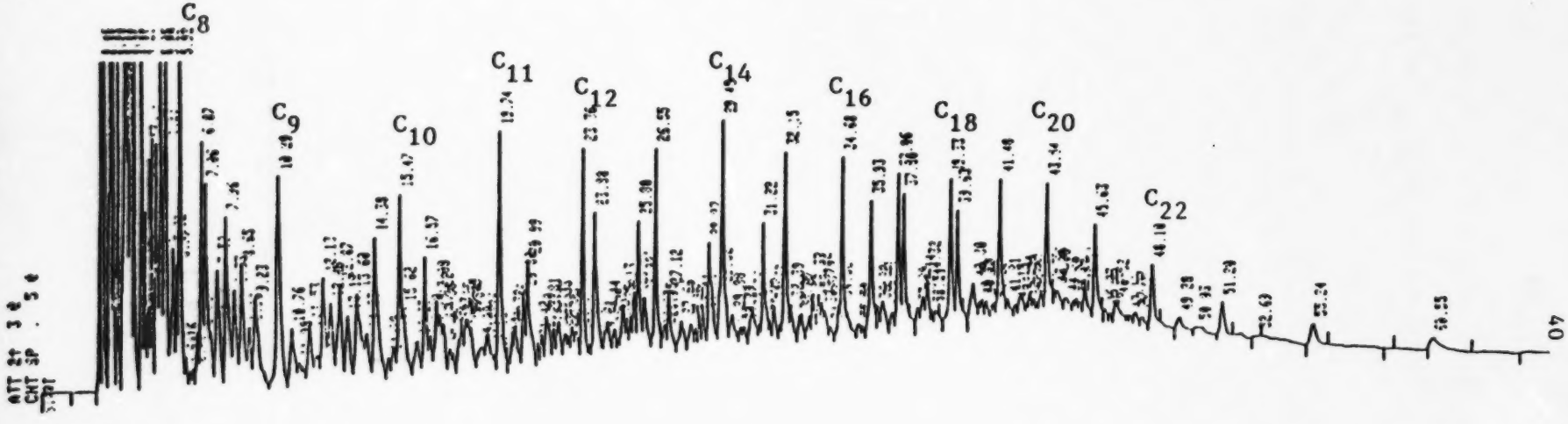



Figure 4.21: Norman Wells Crude Oil

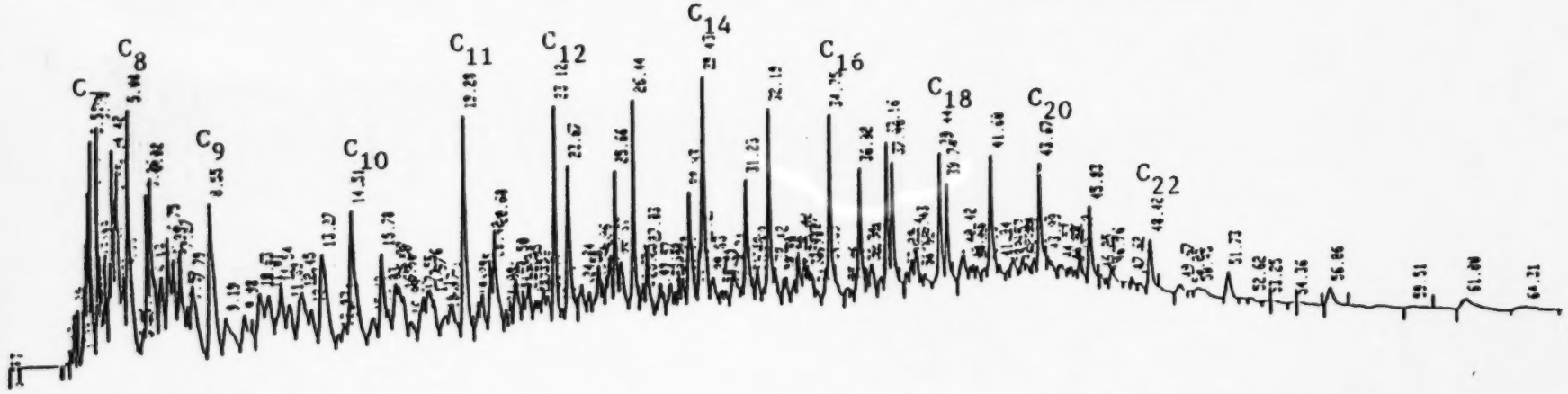



Figure 4.22: Norman Wells Crude (30 min. after the first dosage of Corexit 9527)

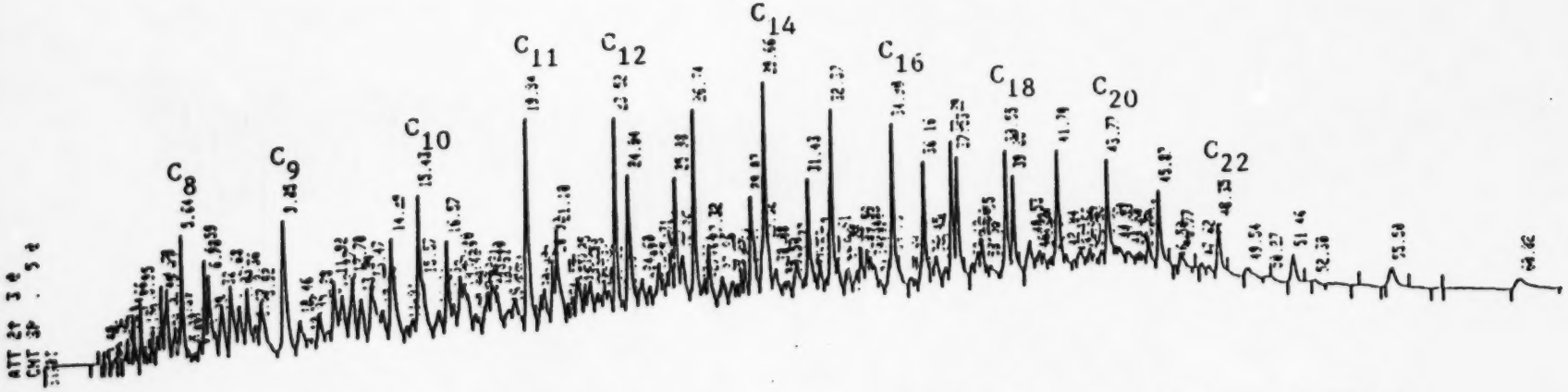



Figure 4.23: Norman Wells Crude (30 min. after the second dosage of Corexit 9527)

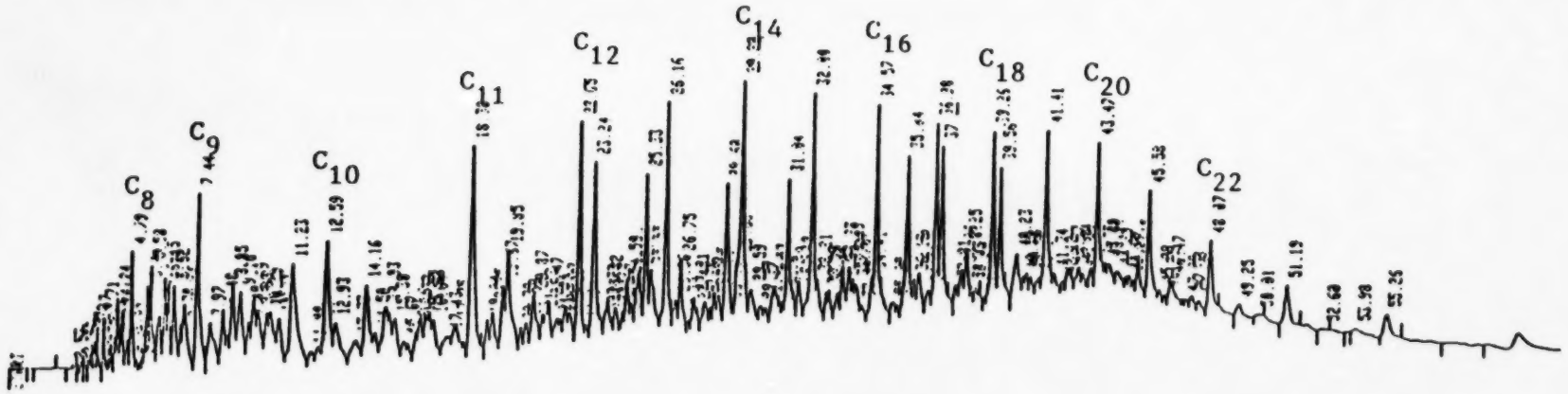



Figure 4.24: Norman Wells Crude (30 min. after the third dosage of Corexit 9527)

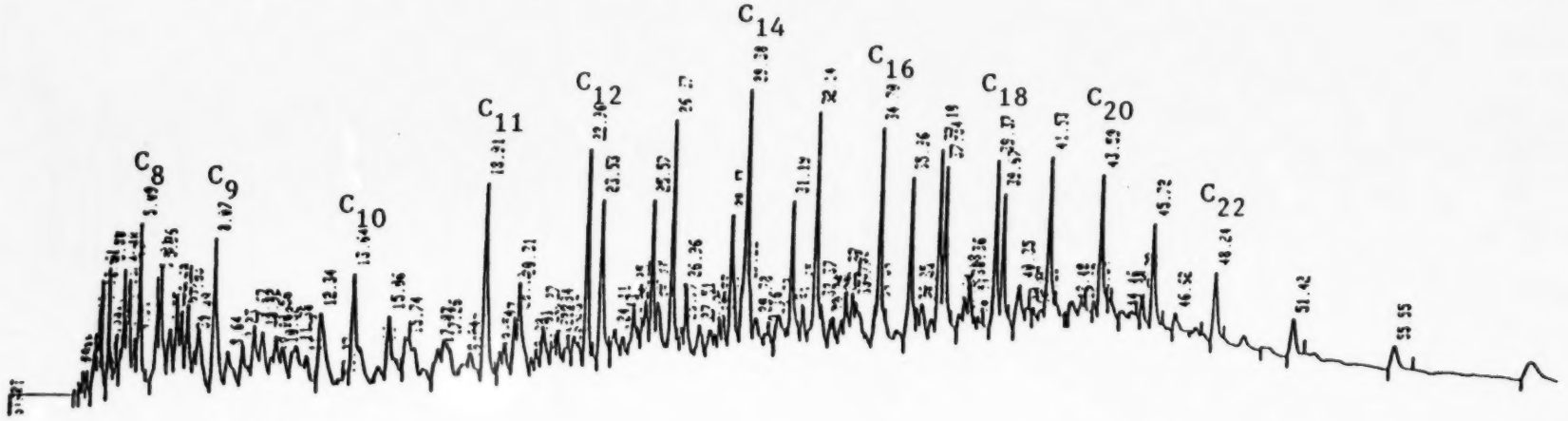



Figure 4.25: Norman Wells Crude (Dispersed oil, 30 min. after the third dosage of Corexit 9527)

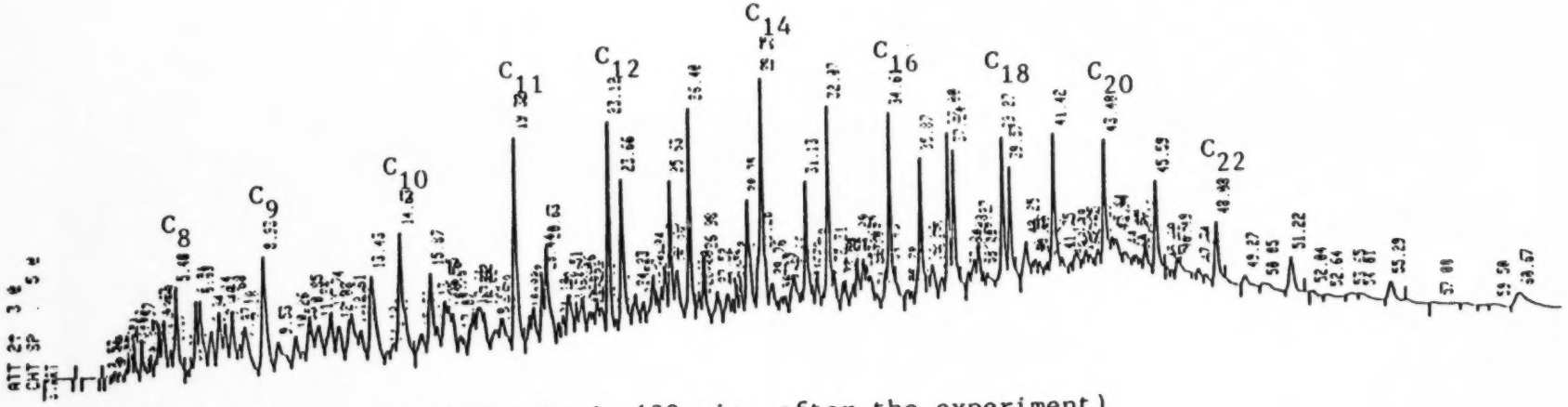



Figure 4.26: Norman Wells Crude (30 min. after the experiment)

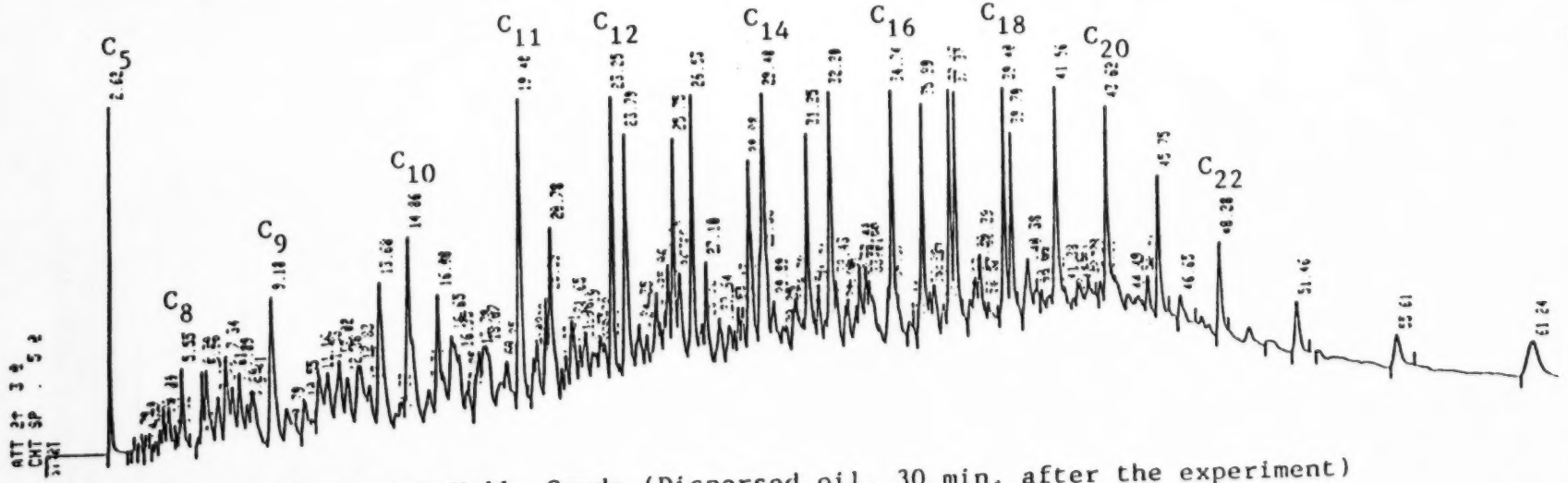



Figure 4.27: Norman Wells Crude (Dispersed oil, 30 min. after the experiment)

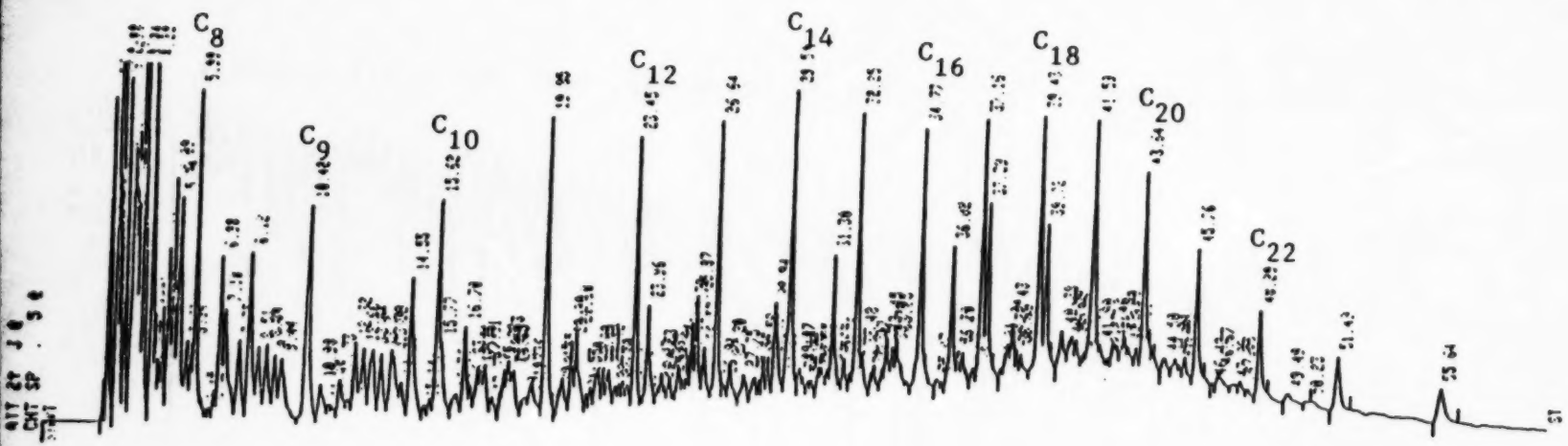



Figure 4.28: EPS Standard

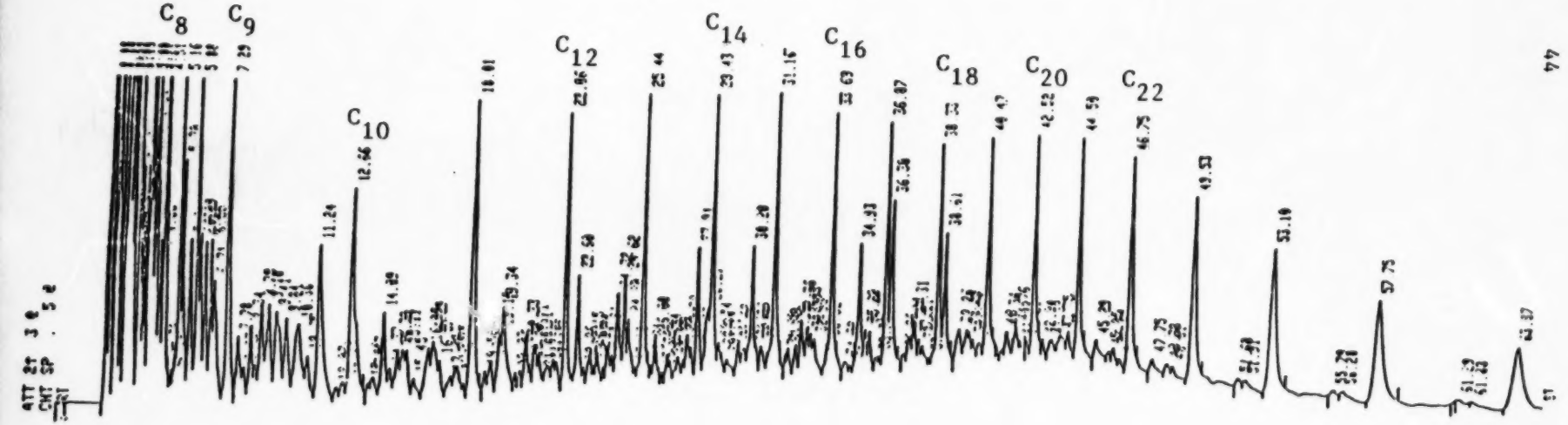



Figure 4.29: 5.6 wt.% wax-EPS Standard

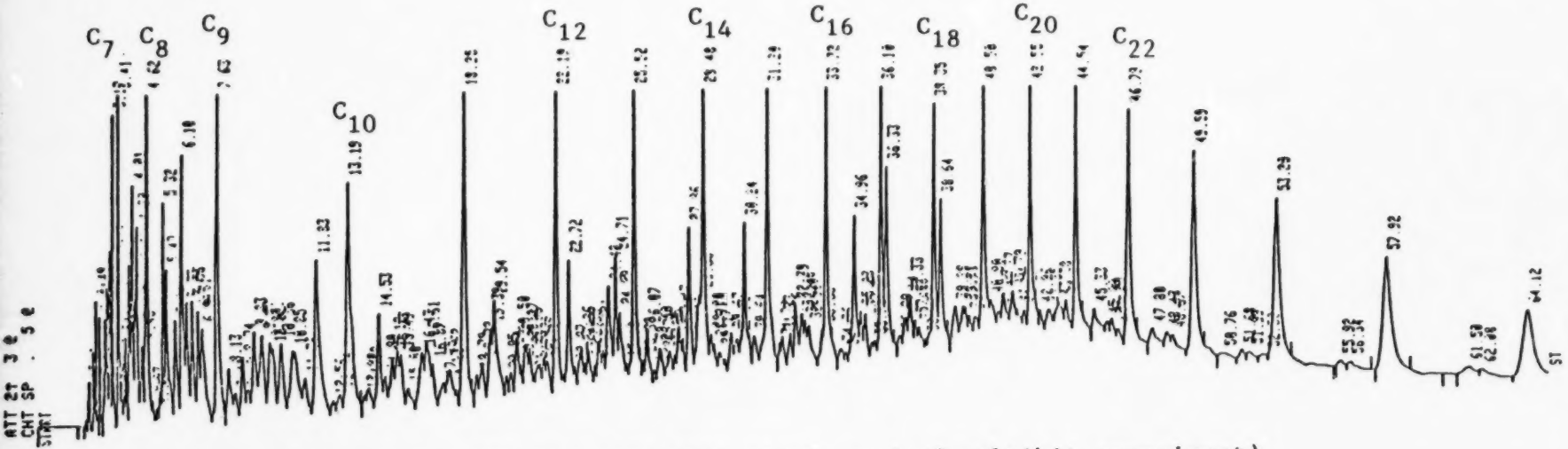



Figure 4.30: 5.6 wt.% wax-EPS Standard (Oil slick, end of multihit experiment)

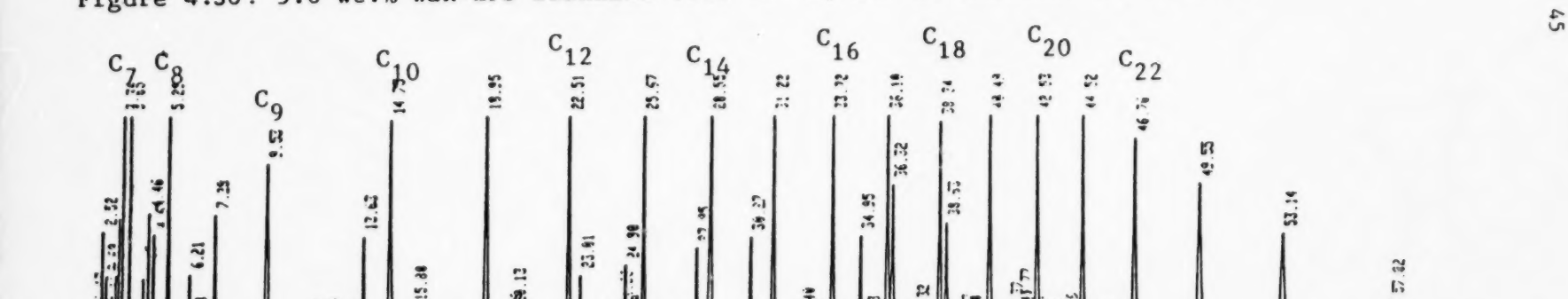



Figure 4.31: 5.6wt.% wax-EPS Standard (Oil slick, end of single dosage experiment)

POOR
QUALITY
ORIGINAL